METALS AND PLASTICS

HUGHES

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THOMAS · P · HUGHES

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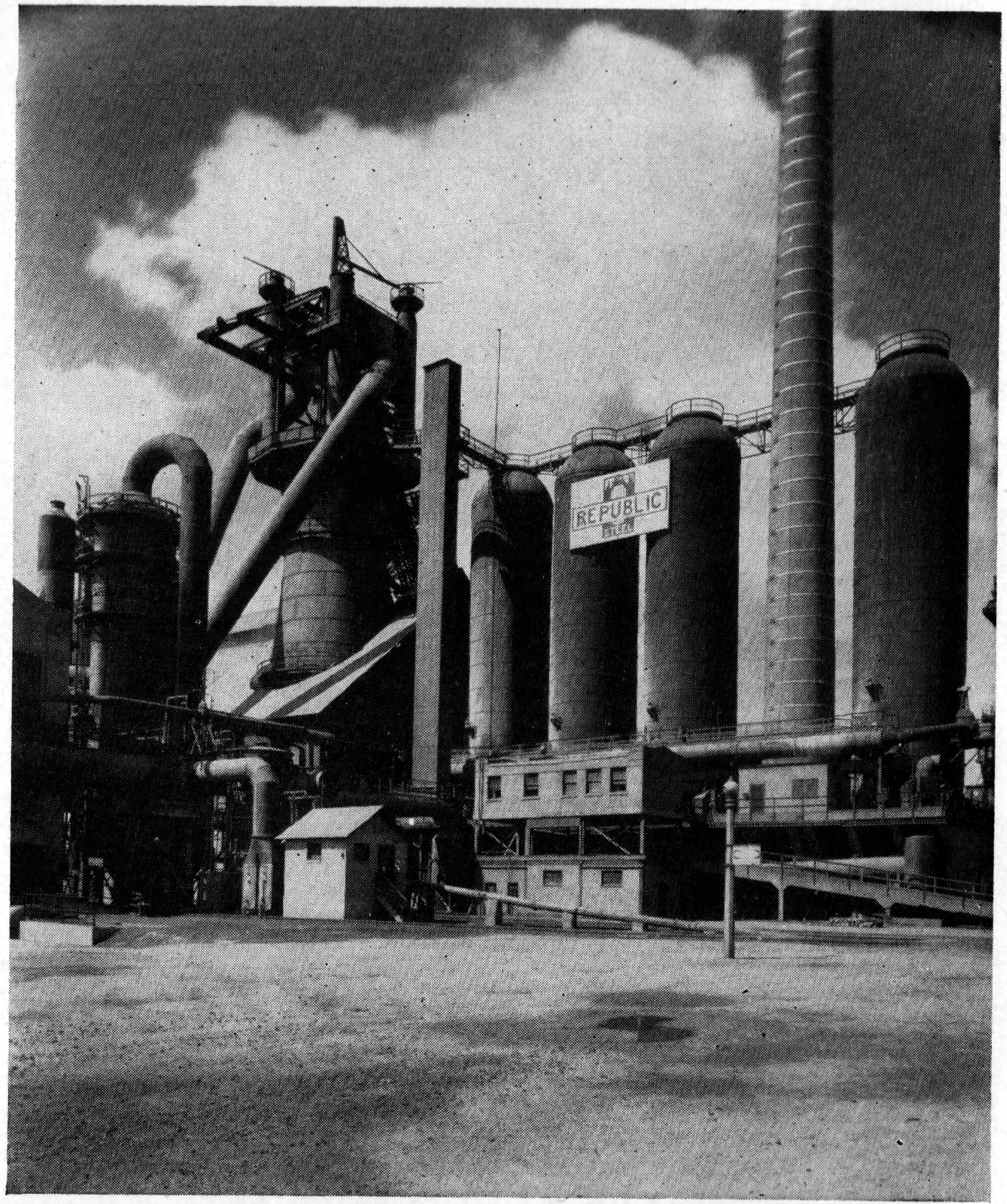
METALS AND PLASTICS



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ONE OF THE WORLD'S LARGEST BLAST FURNACES

METALS AND PLASTICS

Production and Processing

By
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University of Minnesota

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TO MY UNCLES ROBERT, HENRY, AND WILLIAM WHOSE ARTISTRY
WAS AN EARLY INSPIRATION

PREFACE

The ability to appraise the advantages and limitations of materials and of production processes is a highly desirable asset for an engineer to acquire.

Our country has just emerged from an economic state, incident to the prosecution of World War II, which placed upon engineers the urgent necessity of studying and applying the interchangeability of production methods. Critical shortages of manufacturing facilities in particular industries, such as the forging industry, for example, made it imperative that engineers make use of substitute methods so that production might continue without serious stoppage. The success of their efforts was proven by the phenomenal output during the war years as well as by the performance of the manufactured products.

Industry in peacetime as in wartime will continue to expect of engineers an efficient and economical operation of its production facilities. Always, the problem will present itself of manufacturing a functioning part at the lowest possible unit cost. In many instances, this can be achieved best by modifying the design of a part so that it can be made by one process or by one method *as well as* by another; at other times, the selection of a more suitable material will best serve the desired ends.

In either case, the ability to appraise objectively and decide must be based on a wide knowledge of (1) various production methods, (2) mechanical and physical properties of the available engineering materials, and (3) various factors by which mechanical and physical properties of materials may be modified.

The underlying purpose of this volume, then, is to present a comprehensive perspective of manufacturing processes with a detailed study of some of the more common metals, alloys, and plastics so that the student will have an understanding of their fundamental potentialities and a basis for selection.

It is assumed that a student has acquired some knowledge of basic science in chemistry and physics courses before taking a materials course; therefore, the chapters in this volume are arranged in a sequence which will advantageously introduce this new material by relating it to the knowledge gained in those other studies.

For this reason, the first several chapters deal with Metals and Their Internal Structures, Equilibrium Diagrams, and Physical Properties of Metals. These are designed to introduce the student to the basic structures of ferrous and nonferrous metals and alloys and their properties. Then follow chapters on The Manufacture of Iron, The Production of

Steels, Casting Processes, The Mechanical Working of Metals, Nonferrous Metals and Alloys, Welding Processes, The Iron-Iron Carbide Equilibrium Diagram, and The Heat Treatment of Metals. The final chapter classifies the various steels according to the AISI and SAE systems.

The chapter on Plastics classifies these materials and discusses their composition, the processes by which they are formed, and the engineering applications and properties of the various types of plastics.

Glossaries of terms used in the text are furnished in the Appendix. These should prove helpful to the student in all of his engineering work. In addition, ten full-size tables are included, which supplement the textual material throughout the book.

This text is offered with the hope that it will furnish preparation (and incentive) for more specific and related courses in engineering.

Where survey courses in materials and processes are included in the curricula of colleges and universities, this volume offers sufficient material for a full semester. It also provides suitable material to complement industrial laboratory courses offered to sophomores, and preferably juniors, in schools of technology.

The author acknowledges with sincere gratitude the ready and unfailing response of many industrial concerns to requests for information and photographs of equipment. The author also wishes to acknowledge gratefully the loan of the photomicrographs of steel castings by Mr. Herbert J. Blosjo, Metallurgist, Minneapolis Steel Castings Company, and the valuable assistance of Dr. R. L. Dowdell and Dr. H. S. Jerabek of the Department of Metallography, University of Minnesota.

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UNIVERSITY OF MINNESOTA
April, 1947

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METALS AND PLASTICS

CHAPTER 1

METALS AND THEIR INTERNAL STRUCTURES

In this chapter a brief and simple presentation will be made of the importance of metals in general and of their internal structures.

1–1. Development of Use of Metals. In his slow and painstaking progress, man throughout the centuries has implemented his needs and services with whatever materials best served his purpose. Ample evidence points to the predominant use of some one material in certain eras, although doubtless the beginning and ending of these eras overlapped. As more complex needs arose, efforts were made to find new and better materials; some of these were stone, wood, leather, and animal and vegetable fibers. These, as well as gold, silver, and copper, were not only conveniently accessible but also possessed desirable characteristics or properties such as toughness, hardness, strength, brittleness, malleability, flexibility, or lightness.

Since gold and silver, and frequently copper, were obtainable in the pure state, no metallurgical transformation was necessary to adapt them for use. Iron, on the other hand, was hidden in the earth and never found except in association with several impurities, and so its potentialities were only later realized. However, when gold and silver were no longer available and the choice had to be made between copper and iron, it was found that the metallurgical processes required to separate iron from its oxide were less intricate and complicated than those required to produce copper.

At first, both copper and iron—like the precious metals, gold and silver—were rare and were principally utilized as mediums of exchange for commodities and services, or for personal decorations. Subsequently, they were used as weapons. Although iron was long preceded by the other metals, none of the others became so widely used or was destined to fill so great a need or play so important a role in the development of our material civilization, because no other metal has potentialities for such wide range of mechanical properties.

That metals constitute an integral part of our industrial development is evidenced by the fact that they are used to an ever increasing extent; in fact, far more metal has been taken from the earth by man since 1900 than in the whole previous history of mankind. This has given man in the twentieth century a command of the material universe unparalleled in the history of the world. Furthermore, of all the metals fabricated in the

United States (both ferrous* and nonferrous), iron and steel constitute 90 per cent of the total.

1–2. Properties of Metals. Because of our extensive contacts with metals, many of their desirable characteristics are well known to us. For example, we know that they are tough, strong, and hard and that they are capable of being fashioned or shaped, without breaking, while in the hot or cold state. Most of them possess resiliency and luster. They expand when heated and contract when cooled, and resist both corrosion and heat. Their hardness may be changed within wide limits by cold-working or by some form of heat treatment. When cooled rapidly from an appropriate temperature, some steels may be increased from 100 to 200 per cent in hardness and in their ability to withstand a static stress. A steel heat-treated in a certain way may be used to machine or cut the same steel treated in a different way.

The original softness of a metal may be restored by an equally simple process. Nonferrous metals may likewise be greatly improved in strength and hardness by cold mechanical working, by combining with small amounts of other metals, or by heat treatment. Metals may also be formed into wires finer than human hair or into sheets for use as foil. Because of their excellent electrical conductivity, certain metals (copper, aluminum, and silver) perform indispensable functions as transmitters of electrical energy, while the high magnetic permeability of iron and its alloys renders them important for use in magnetic circuits.

Some metals—such as copper, aluminum, zinc, lead, nickel, and iron—find application in their commercially pure state. Engineering requirements are more adequately met, however, when metals are combined in various proportions either with other metals or with nonmetals to constitute **alloys.** As preceding eras are designated *Stone Age*, *Bronze Age*, or *Iron Age*, surely the twentieth century may appropriately be called the *Alloy Age*. It is said that there are well over 5,000 different alloys in commercial use today. The steel industry alone is said to produce and sell some 100,000 different items.

1–3. Alloys. An alloy is a metallic substance consisting of two or more elements which are wholly or partly soluble in each other in the liquid and solid state. When one element is added to a plain carbon steel in an amount sufficient to alter the mechanical or physical properties, the alloy is known as a binary alloy. Example of this would be nickel, chromium, vanadium, or molybdenum structural steels. When two metals such as chromium-nickel or silicon-manganese are added to steel or when copper and manganese are added to aluminum, the alloy is called a ternary alloy.

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*From *ferrum*—Latin for iron.

Alloys composed of three or more alloying elements are known as quaternary alloys. The number of alloys possible by combining the metals in varying proportions is almost unlimited.

The combining of two or more metals, or a metal and a nonmetal such as iron and carbon, produces physical and mechanical properties which differ widely from those of the component metals. While some specific property is obtained by the addition of alloying elements, such a result is often achieved at the expense of some other property. Thus, the softness and ductility of tin and copper are impaired when these metals form bronze, although the strength of bronze is greater than that of either tin or copper. Iron and nickel alloys are more magnetic at low magnetizing force than either iron or nickel. Copper, manganese, and aluminum form an alloy capable of being magnetized, although none of the component metals can be magnetized. Silicon causes difficulty in forging when added to steel; yet it makes low-carbon steel highly desirable for use in transformer cores and in generator and motor parts because of its high electrical resistance and magnetic permeability. Carbon, added in small amounts to iron, increases the iron's hardness and susceptibility to cold-working and heat treatment, but reduces its ductility or toughness. The high electrical and thermal conductivities of aluminum, copper, and silver are impaired by alloying with other metals, although there may be an increase in strength and hardness. A study of the theory of alloying and of the influence of different alloying elements in various amounts on the physical and mechanical properties of metals requires a deep and thorough knowledge of basic metallurgy and cannot be adequately covered in this text.

1–4. Metallurgy. Metallurgy is that specialized branch of science concerned with the extraction of metals from their ores and with their refining and adaptation to industrial needs. Its understanding requires a knowledge of the fundamentals of physics and chemistry, since such concepts as compounds, mixtures, solutions, pressures, phases, components, and constituents are involved.

Chemical metallurgy applies specifically to the smelting and refining of metals, while *process metallurgy* relates to the mechanical operations necessary in the shaping and processing of metals. The branch that deals with the composition, internal structures, laws, theories, and constitution of solid metals and alloys is known as *physical metallurgy* or *metallography.*

In their usable forms, both ferrous and nonferrous metals are products representing a series of operations, each of which involves many chemical reactions. Some of these reactions are difficult because (1) they are reversible ($Fe_2O_3 + 3CO \rightleftarrows 2Fe + 3CO_2$), and, therefore, conditions must be closely controlled; (2) they occur in closed furnaces or retorts and are thus difficult to control; and (3) they occur at elevated temperatures ranging over wide limits.

The series of metallurgical operations involved in the production and development of usable commercial metal products may be summarized as follows: mining, ore dressing, smelting or reduction, refining, alloying, casting, shaping and processing or heat treatment.

1–5. Metal Structures. Except for a few amorphous substances—glass, amber, rubber, and plastics are examples—all solid bodies, such as metals and minerals, consist of minute cells or crystals. Since these crystals (or crystalline grains, as they are more commonly called in metallurgy) influence and determine the mechanical properties and behavior of metals, the conditions under which they form and the methods of their control in subsequent operations are of great importance. Only a brief summary of these factors may be given here; for more exhaustive study, the student is urged to consult other texts devoted exclusively to the subject.

1–6. Mechanism of Solidification of Metals. It is well known that saturated steam at 212F occupies more than 1,700 times the volume of an equal weight of water at the same temperature. This fact proves that molecules of gases and vapors are farther apart than are those of liquids. Because they are not restrained by strong cohesive forces in their incessant and violent state of agitation they tend to separate as far from one another, as the walls of the container will permit.

That even great pressures produce little diminution in the volume of a liquid proves that the free space so characteristic of gases is relatively unimportant in liquids. This is evidenced by the smaller volume occupied by substances which have condensed into the liquid state. Although the molecules of a liquid are still in rapid motion and possess considerable freedom of movement, they exhibit a much greater tendency to cohere and form groups than do the molecules of a gas. Nevertheless, though the molecules of liquids are much more restricted by cohesive forces than the molecules of gases, constant shifting of the bonds between them is evidenced by the fluidity of liquids and by the diffusion which takes place slowly between liquids capable of mixing (e.g., water and alcohol).

When the temperature of the liquid is further lowered, the freedom of shifting bonds becomes less; and the groupings grow by attracting more and more free molecules to themselves. With further lowering of the temperature, the thermal energy of the molecules is no longer sufficient for them to shift and move freely over one another. The result is that the substance solidifies or crystallizes.

The excess of energy possessed by the liquid over that of the solid at the same temperature is known as *latent energy* or *latent heat of fusion*.

When the latent energy decreases to an extent which permits the substance to crystallize, the atoms or molecules become *fixed* at atomic centers.

This crystallization, however, does not imply complete absence of motion. It means only that the mean free motion is curtailed and that, essentially, the movement is a vibration about the equilibrium positions of the atoms or molecules. The *amplitude* of the vibration and, consequently, the kinetic energy of the constituent atoms or molecules varies in direct proportion to the temperature on all levels above absolute zero. The *frequency* of vibration, however, does not vary greatly with temperature.

In chemistry it is assumed that all matter is composed of molecules and that the molecules of any particular substance are all alike in nature and in mass. Each molecule is made up of a number of smaller units or atoms. As far as is known, all metallic elements are monatomic; that is, they consist of molecules containing only one atom. For this reason the atom is considered the unit of which crystals of solid metals are composed.

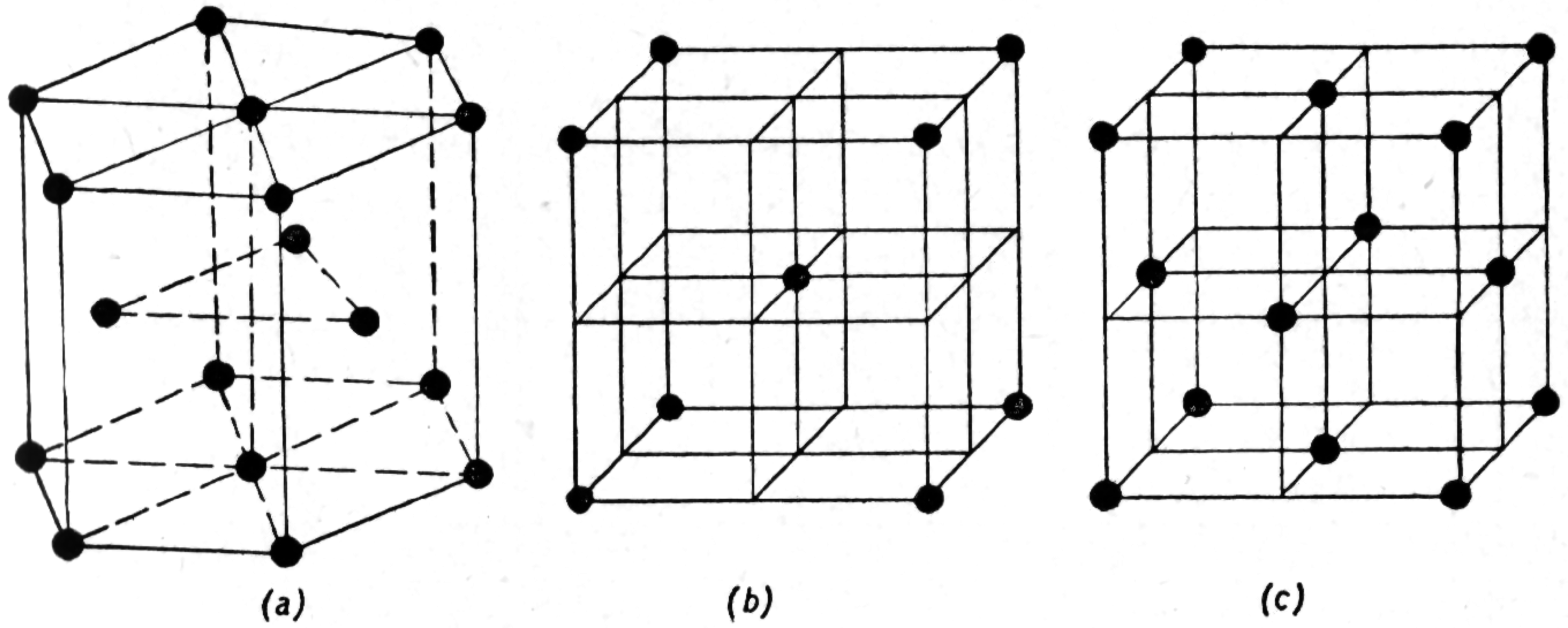
(a) (b) (c)

FIG. 1–1. Crystal structure of some common metals. At (*a*), hexagonal close-packed pattern; at (*b*), body-centered alpha (or delta) iron; and at (*c*), face-centered gamma iron.

Except for the few amorphous substances mentioned above, all solid bodies possess a remarkable ability to arrange their atoms or molecules in a definite geometrical and repetitive relationship and to form crystals of characteristic types. Thus, sodium chloride crystallizes from the liquid to form cubical crystals, while sulphur forms diamond-shaped crystals that belong to the rhombic system. Metals crystallize according to a number of configurations, although most metals crystallize according to the three typical patterns shown in Fig. 1–1. Since these crystals may be considered as being composed of a latticework with the atoms in regular order at the intersections, the basis upon which the crystal is constructed is called a *space lattice*.

For the most usable metals, these space lattices are of a body-centered cubic, a face-centered cubic, and a hexagonal close-packed pattern. From Fig. 1–1 it will be seen that in the body-centered cube the atoms are arranged at each corner with 1 in the center or body of the cube. The corner atoms are shared by 8 adjacent cubes; and, therefore, the body-centered cubic unit contains only 2 atoms, although there are 9 atoms involved.

In the face-centered cubic lattice, the atoms are similarly arranged at each corner of the cube, but with 6 additional atoms placed individually in the center of each face. Although 14 atoms are involved, each corner atom is shared by 8 adjacent cubes, and the atoms on the faces are each shared by other cubes. By this arrangement ⅛ of each corner atom and ½ of each atom on the faces belongs to the cube unit, making a total of 4.

As shown in the arrangement of the atoms in the hexagonal close-packed lattice, 1 atom occupies each corner of the prism with 1 in the geometric center. Each atom is similarly, although not equally, related and shared by adjoining crystals.

It is interesting to observe in Table 1–1 that most of the common metals fall into three distinct classes. The type of crystal lattice very largely influences the malleability and ductility as well as the thermal and electrical conductivities of the metals.

TABLE 1–1

CRYSTAL LATTICES OF COMMON METALS*

Body-Centered Cubic	Face-Centered Cubic	Hexagonal Close-Packed
Chromium	Aluminum	Beryllium
Iron	Copper	Cobalt
Molybdenum	Gold	Magnesium
Tantalum	Lead	Titanium
Tungsten	Nickel	Zinc
Vanadium	Platinum	Zirconium
	Silver	

**ASM Handbook* (1939 ed.).

Metallic crystal structures are analyzed by means of X-rays of known wave length. By their use, it is possible to measure the spacing of atomic planes in the unit crystal as well as the arrangement of the atoms. Grain size, identification, and distribution of metallic constituents are observed by means of optical microscopes when specimens, after polishing and etching, are magnified from 100 to well over 2,000 diameters. A permanent record of the grain structure may also be obtained by photographing the image; this is called a *photomicrograph*. A photographic record of the crystal lattice, produced by means of X-rays or gamma rays, is called a *radiograph*.

1–7. Allotropic Modification. When an element exists in more than one form in the same physical state, these forms are said to be allotropic modifications of the element. Carbon, for example, is an allotropic form of a diamond. Certain metals also exist in some range of temperature with one crystal structure, which, upon heating or cooling to another temperature, will change into a different lattice. While the composition remains unaltered, the mechanical, chemical, and electrical properties usually change greatly.

The most notable and most familiar illustration of allotropic modification is that of iron, which at normal temperatures has a body-centered cubic structure. If heated to 1670F, it changes to a face-centered structure, which it retains until at 2550F, when it reverts to the body-centered form. These allotropic forms of iron are known respectively as alpha, gamma, and delta. The significance of these changes in relation to the heat treatment of steel will be discussed more fully later.

1–8. Recrystallization. When metals are subjected to some form of mechanical work at normal temperatures, the external force causes a distortion of the crystals along certain planes, known as *slip planes*. The plastic deformation of the metal on these planes also produces a condition of strain-hardening, varying in intensity directly with the amount of deformation produced. Slip lines or slip bands on the surface of plastically deformed metals, visible under the microscope as parallel lines, indicate that deformation of this type has occurred by the displacement of blocks of crystals having similarly oriented planes. If such a metal is heated to an appropriate temperature and held for a sufficient time, the strain will be eliminated, and the grains will assume their normal, unstrained, equiaxial shape.

That metals thus recrystallize is a distinct advantage, since, in such fabricating processes as the cold-drawing of brass or steel shells, the metal is strain-hardened and, consequently, becomes less ductile. If strain is continued, the part will fail along the weakest plane. Before further work is possible, the ductility must be restored by heating to the recrystallizing temperature.

1–9. Compounds and Mixtures. Substances whose constituent parts combine in such a manner that they cannot be separated by mechanical means or identified as separate entities are known as compounds or intermetallic compounds. The mass is homogeneous throughout, and molecules are all of the same kind. Such compounds have definite chemical formulas; for example, iron and carbon form carbide, Fe_3C; copper and aluminum form copper aluminide, $CuAl_2$; and magnesium and silicon form magnesium silicide, Mg_2Si. The components of a compound are always present in the same proportion for any compound, while the components of alloys and solutions vary greatly in their proportions. However, alloys and solutions, like compounds, are mechanically inseparable.

Substances composed of constituents whose identity is retained and which can be separated by mechanical means are known as mechanical mixtures.

Intermetallic compounds play an exceedingly important part in our alloys.

1–10. Solid Solutions. The manner in which solutions freeze indicates that they fall into two distinct classes: those in which the constituents are soluble in the liquid and solid state, and those in which solubility is complete in the liquid state but is incomplete in the solid state. Liquids such as alcohol and water are soluble in each other in all proportions. Salt is soluble in water but insoluble in ice. The solubility of metals in one another is strictly analogous to the solubilities of liquids. Metals may be completely soluble in each other in the liquid or in the solid state or in both. A solid solution is identical with a liquid solution except that it does not appear to be fluid. It is a true solution of the components which are in the solid form. Various diagrams known as constitution diagrams, which show the characteristics of different types of solutions, are given in Chapter 2.

1–11. Grain Structures. Crystal units, which form simultaneously at a large number of crystallizing centers or nuclei, grow along certain planes much more rapidly than on others. As shown in Fig. 1–2, the growth of a cubic crystal takes place by projection into the melt in 3 directions at right angles corresponding to the 6 faces of the cube. Because of their resemblance to a pine tree with its central trunk and branches growing out from the sides parallel to one another, such crystals are called *dendrites* (meaning treelike).

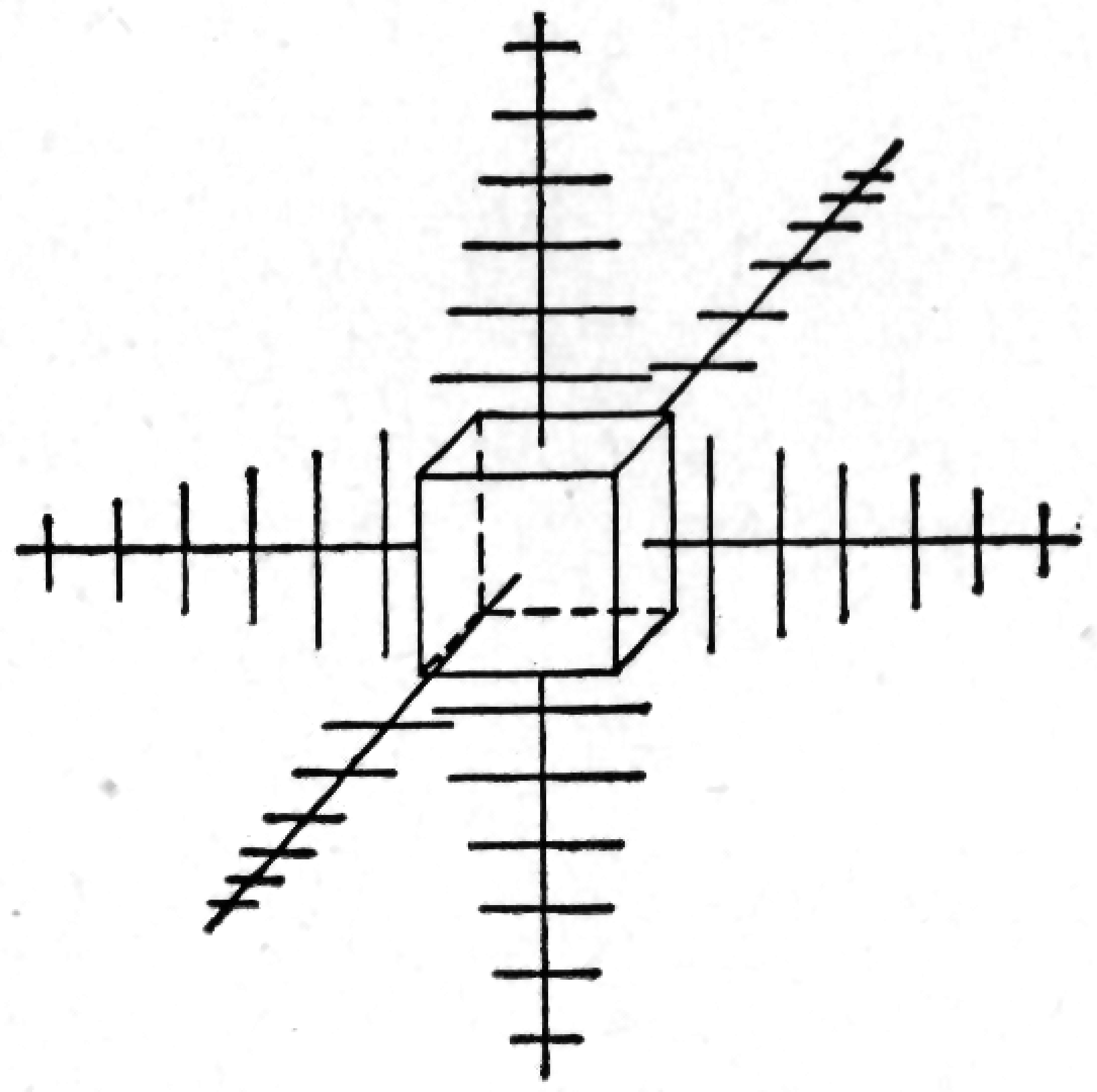

FIG. 1–2. Dendritic (treelike) growth of unit crystal cell.

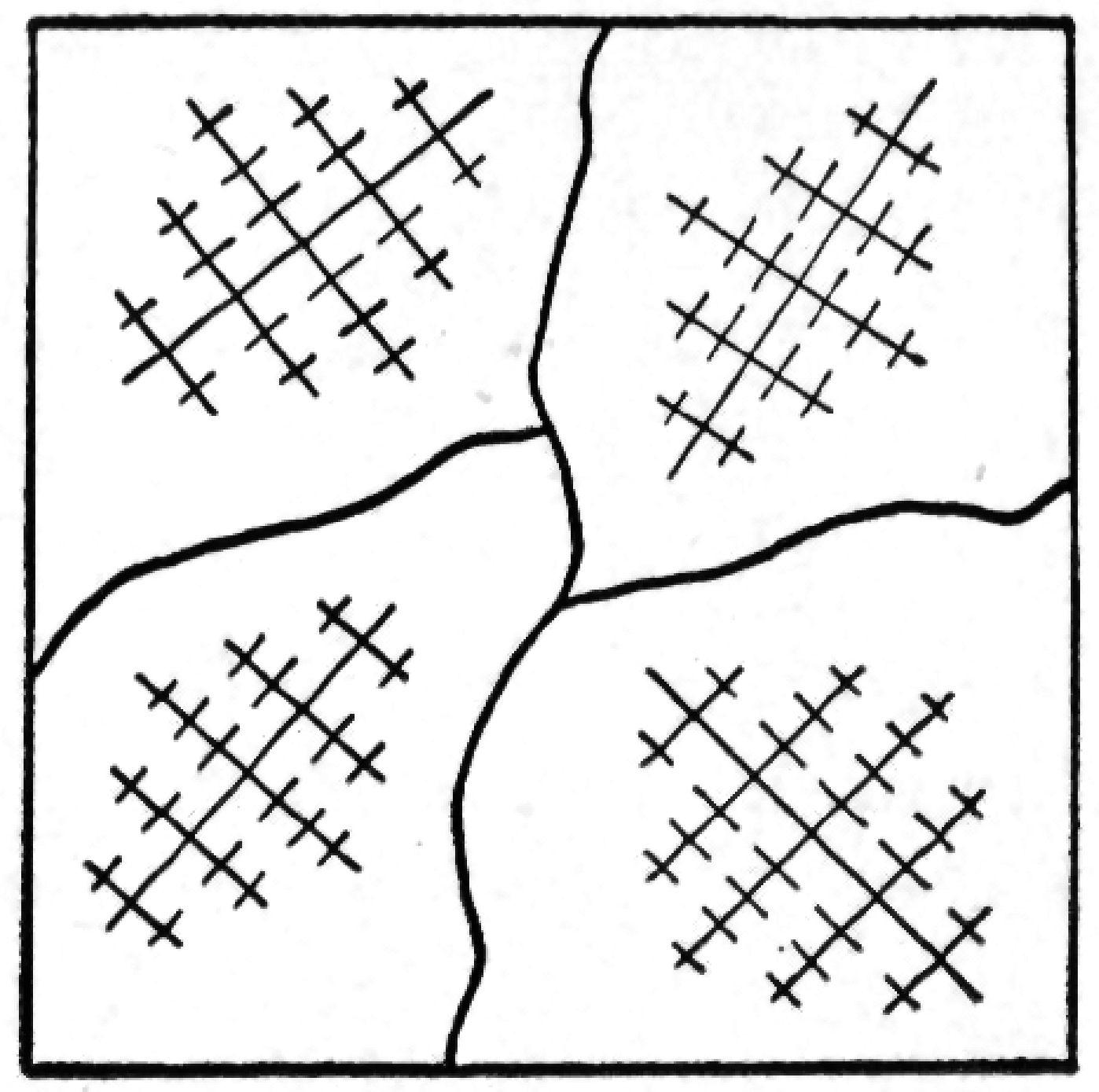

FIG. 1–3. Structural formation of grains from crystals.

Since the crystals extend their growth rapidly in all directions from various centers in the presence of liquid metal, they eventually contact other crystal aggregates which have a number of different orientations, so that, when all the melt has crystallized, an irregular boundary has been established between them, as shown in Fig. 1–3.

Aggregates composed of a large number of crystal cells are called *crystalline grains*, or just *grains*. While the internal structure of a grain consists of an orderly arrangement of atoms, its exterior shape is determined by the number and manner of the contacts it makes with other grains. Fig. 1–4 shows a photomicrograph of pure iron deeply etched with acid to show its cubelike internal structure. Fig. 1–5 shows the random formations of grains.

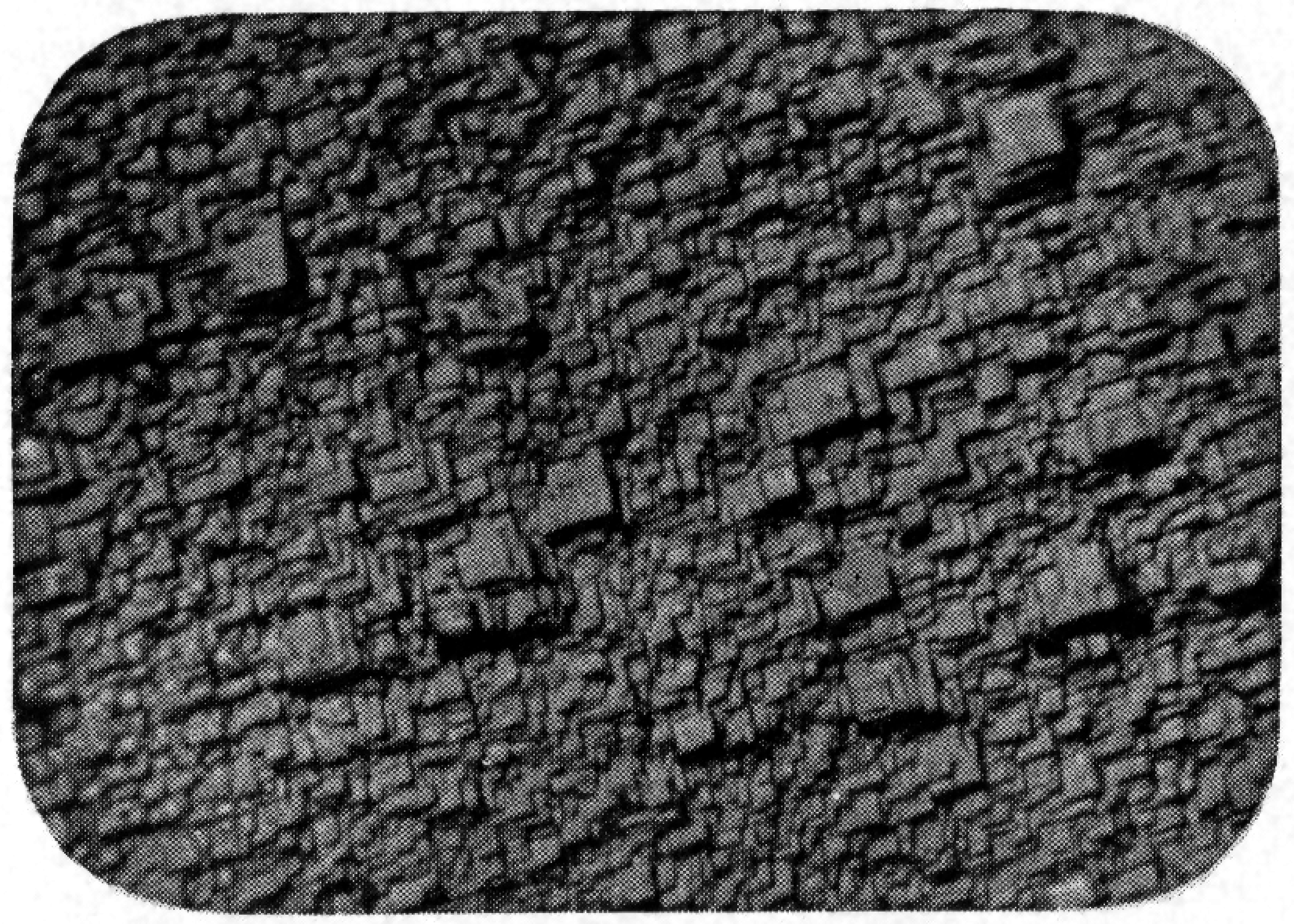

FIG. 1–4. Low-carbon (ingot) iron, deeply etched with concentrated HNO_3 to show cubic structure of crystals within one grain. X900. (Courtesy of School of Mines and Metallurgy, University of Minnesota.)

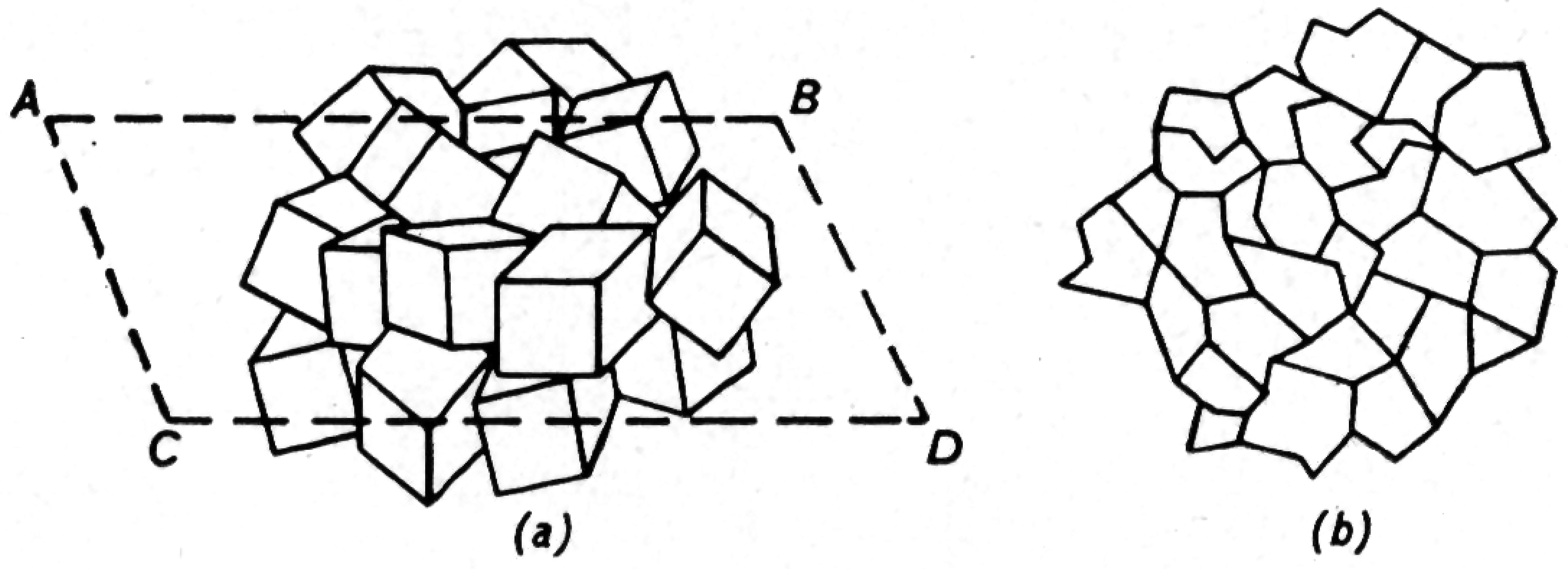

FIG. 1–5. Schematic representation of formation of crystalline grain structure. At (*a*), random orientation of crystals; and at (*b*), section of plane *ABCD* as seen from above.

Since the many contacts made by these crystalline grains are with aggregates of different orientation, the grains of a metal vary greatly in size and are many-sided or polyhedral. The size of grains is determined by a number of factors, among which are the number of crystallizing nuclei, the temperature gradients within the metal, the rate of cooling through the solidification range (slow cooling facilitates large grains), and the purity of the metal.

Because the mechanical properties of steels and their response to heat treatments are influenced by grain size, practices have been developed to control and standardize the grain size, as will later be shown. Methods of control include chiefly the use of nuclei-forming elements, for which purpose aluminum is commonly added during the production of the steel. The alloys with vanadium, molybdenum, nickel, or tungsten also are less susceptible to grain growth during subsequent operations, such as forging and heat-treating, than are unalloyed steels. Likewise, thorium is added to tungsten (used as lamp filaments) to prevent grain growth during high operating temperatures. It is advantageous to the formation of small grains to have the crystallization proceed simultaneously from a large number of crystal nuclei, since the greater the number of grains, the smaller their size. With a very slow and controlled cooling rate, metals may be caused to crystallize into single grains measuring several inches in width and length.

Smaller grains, which still are large enough to be seen with the naked eye, can also be produced. Examples of these are the grains of zinc on a galvanized sheet. Bronze or brass door handles which have been etched by the sweat of human hands also frequently reveal the grain structure. Normally, the aid of the microscope is required to analyze the grain structure.

Grain growth not only takes place rapidly in the presence of molten metal but also continues, only more slowly, even after the metal has become completely solid. Therefore, in addition to the above factors, grain size is also influenced by the cooling rate subsequent to solidification. See Fig. 11–1.

The closest approach to each other of the atoms of a unit cell or crystal of (alpha) iron is of the order of 2.478×10^{-8} cm.* The length of a side of the unit cell of iron is 2.861×10^{-8} cm, of copper 3.60×10^{-8} cm, and of aluminum 4.04×10^{-8} cm, respectively, at 68F (20C).

QUESTIONS AND PROBLEMS

1. Define an alloy, a binary alloy, a ternary alloy, a quaternary alloy.
2. Name the possible components of alloys.
3. List the properties which distinctly apply to metals.
4. Analyze the advantages and disadvantages of alloying.
5. Classify the various phases of metallurgy.
6. Define "amorphous."
7. Define "crystallinity."
8. Which of the following are amorphous and which are crystalline substances: rock candy, marble, bronze, plastics, cast-iron, aluminum, glass, steel, sulphur, amber, lead, pitch?

[Metals Handbook] (1939 ed.).

9. What fundamental factors characterize metals in the molten state? In the solid state?
10. Define "latent heat of fusion."
11. Which state of molecular activity signifies the greater degree of energy of metals and liquids?
12. Trace the molecular activity of metals during their period of solidification.
13. Define "amplitude" and "frequency."
14. Describe the following space lattices: hexagonal close-packed, face-centered cubic, and body-centered cubic.
15. Name four metals which possess each of the lattices named in Question 14.
16. Define "grain" and "crystal."
17. What is the basis for the formation of dendritic grains?
18. What is the influence of the number of crystal nuclei on the size of the grains?
19. List the factors influencing grain size of metals.
20. What characteristics of metal structures are revealed by radiographs and photomicrographs?
21. Explain the mechanism by which work-hardened metals become softened when reheated.
22. What condition principally differentiates solid solutions and liquid solutions?

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CHAPTER 2

EQUILIBRIUM DIAGRAMS

2–1. Introduction. In the preceding chapter it was pointed out that metals combine in various ways to form alloys whose mechanical properties are often quite different from those of the constituent metals. In this chapter a study is made of how these metals combine and of their internal structure.

It was also stated that alloys are classified according to the number of metals of which they are composed, as follows: two metals, binary alloys; three metals, ternary alloys; and four metals, quaternary alloys. Alloys may also be classified as mechanical mixtures, solid solutions, or chemical compounds, according to the manner in which the constituent metals combine.

Since the structural changes effected by the formation of various alloys affect the mechanical properties or the behavior of the alloy, it is desirable to know what factors control these conditions in order that alloys may be produced to meet various requirements of strength, ductility, heat, and corrosion resistance or to provide desirable electrical and magnetic properties.

An alloy may be studied (1) during its solidification and cooling, by a thermal analysis in which changes in composition (solubility) are plotted against changes in temperature; (2) after its solidification, by a microscopic examination of the structure; or (3) by an X-ray analysis of its crystal lattice.

When data relative to the slow cooling of metals and alloys are plotted, we obtain what are known as constitution or equilibrium diagrams. From these may be learned not only the relative solubility of the constituents during their solidification under equilibrium conditions, but also their structural composition in the solid state.

In the construction of these diagrams, it is customary to plot the temperature as the ordinate and the composition as the abscissa. Usually the compositions are expressed in weight per cent or, sometimes, in atomic per cent. The lower left-hand corner of the diagram represents 100 per cent of metal *A*, and the lower right-hand corner represents 100 per cent of *B*. The total concentration of the metals along the base for any composition is the total sum of the percentages of the constituents.

The curve or line on the diagrams which indicates the temperature at which solidification begins is designated *liquidus*, while the temperature curve indicating the completion of solidification is called *solidus*. This means that alloys of any composition at a temperature above the liquidus consist of a single phase, the melt. Below the solidus, the alloy is completely solid; and, between the liquidus and solidus, the alloy consists of solid in equilibrium with the liquid.

When the alloy is heated, the solidus becomes the temperature at which melting begins, and the liquidus the temperature at which the alloy is completely molten.

Lines drawn perpendicular to the base line to represent any given composition are called *concentration verticals*. Horizontal lines drawn to represent a constant temperature are called *temperature horizontals*.

2–2. Solidification of Pure Metals. Some of the phenomena characterizing changes in physical state, such as liquid ⇆ solid, are well known. For example, water at standard atmospheric pressure becomes steam at 212F and a solid at 32F. Gases may also be condensed to liquids by increased pressure at normal temperatures, while others, to become liquefied, must be cooled as well as compressed. The temperatures at which these liquid-solid transformations take place are known as *critical temperatures*. Changes in the state of pure metals and alloys at the solidification temperature are also accompanied by a thermal manifestation which is evident when time-temperature cooling (or heating) curves are plotted from data. Such a curve, derived from a study of the freezing of a pure metal, is shown in Fig. 2–1.

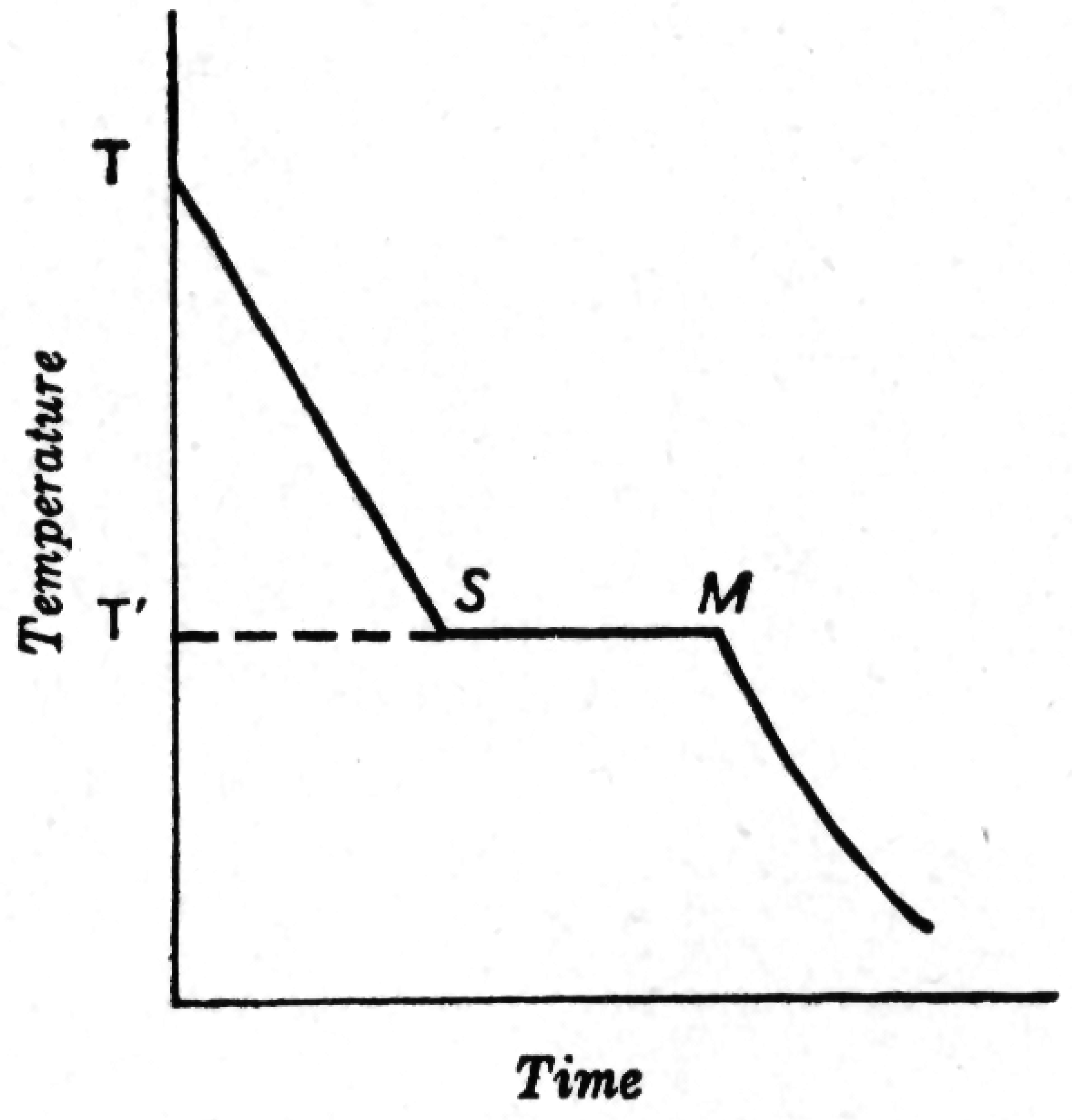

FIG. 2–1. Time-temperature cooling curve of pure metal.

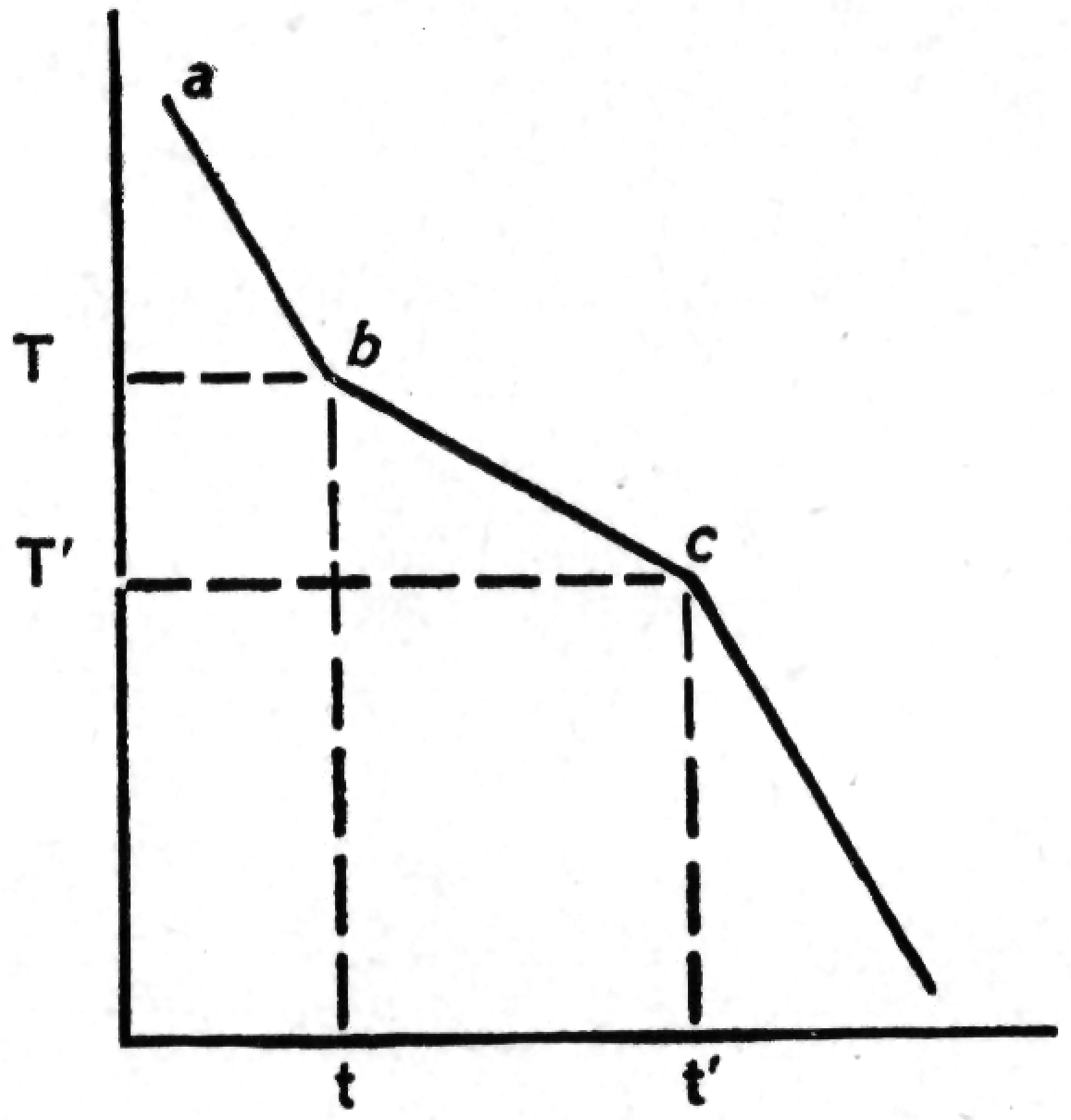

FIG. 2–2. Time-temperature cooling curve of solution of two metals, mutually soluble in both liquid and solid state.

A reference to Fig. 2–1 will make it clear that the cooling of the molten metal proceeds at a uniform rate between temperature T and T'. As freezing begins at T', a discontinuity in the curve is noted as the cooling is arrested until all of the melt is solidified and its latent heat of fusion has been removed. During the period of solidification indicated by the horizontal portion SM, the system consists of two phases—liquid and solid in equilibrium. As solidification is completed, a normal cooling rate is again resumed as shown by the lower portion of the diagram.

2–3. Solid Solution Alloys. A time-temperature cooling curve for a *solution* of two metals mutually soluble in the liquid and solid state possesses characteristics somewhat different from those indicating the freezing of a pure substance. These characteristics are shown in Fig. 2–2. The portion of the curve *ab* is comparable to that of the pure metals and indicates normal cooling with decreasing temperature. At temperature T, the slope of the curve is altered as the freezing begins at b and ends at c or T'. It will be observed that solidification has proceeded, not only over an interval of time t to t', but also over a range of temperature T to T'. Since metal A and metal B are mutually soluble in both liquid and solid states, the melt that solidifies in the temperature range T to T' is a solid solution whose composition varies throughout the solidification range of temperatures.

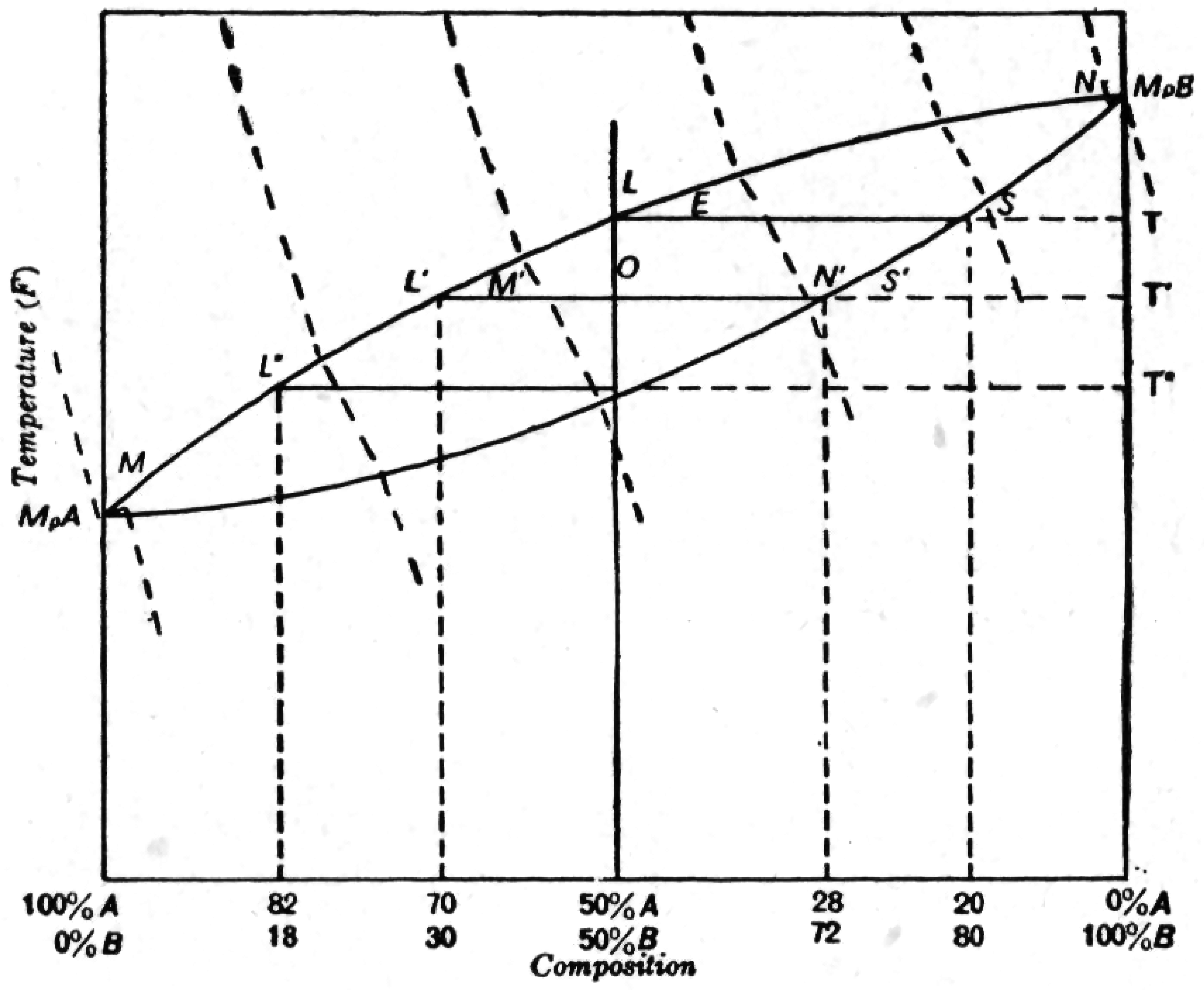

FIG. 2–3. Equilibrium or constitution diagram of two metals, mutually soluble in both liquid and solid state.

If a series of cooling curves for a number of solid solution alloys of different percentage compositions were combined, a curve drawn through the temperatures indicating the beginning and completion of freezing of the alloys would produce a diagram known as an equilibrium or constitution diagram. This is shown in Fig. 2–3.

For the interpretation of this diagram, we may study the cooling characteristics of an alloy containing 50 per cent of metal A and 50 per cent of metal B. Such a diagram represents the cooling of copper-nickel or gold-silver alloys, since these metals are mutually soluble in both liquid and solid states.

Above the liquidus *MLN*, the alloy is a homogeneous liquid solution and consists of a single phase. At *E*, temperature *T*, a solution of the two metals solidifies with a composition as indicated by *S*, and is in equilibrium with the liquid whose composition is shown at *L*. Because of the higher freezing temperature of metal *B*, the composition of the first melt to freeze, shown at *S*, is approximately 20 per cent of *A* and 80 per cent of *B*. Since the composition of the solid continually changes, it is obvious that the composition of the remaining melt also changes. The composition of the first solid is found by projecting a temperature horizontal until it intersects the solidus at *S*.

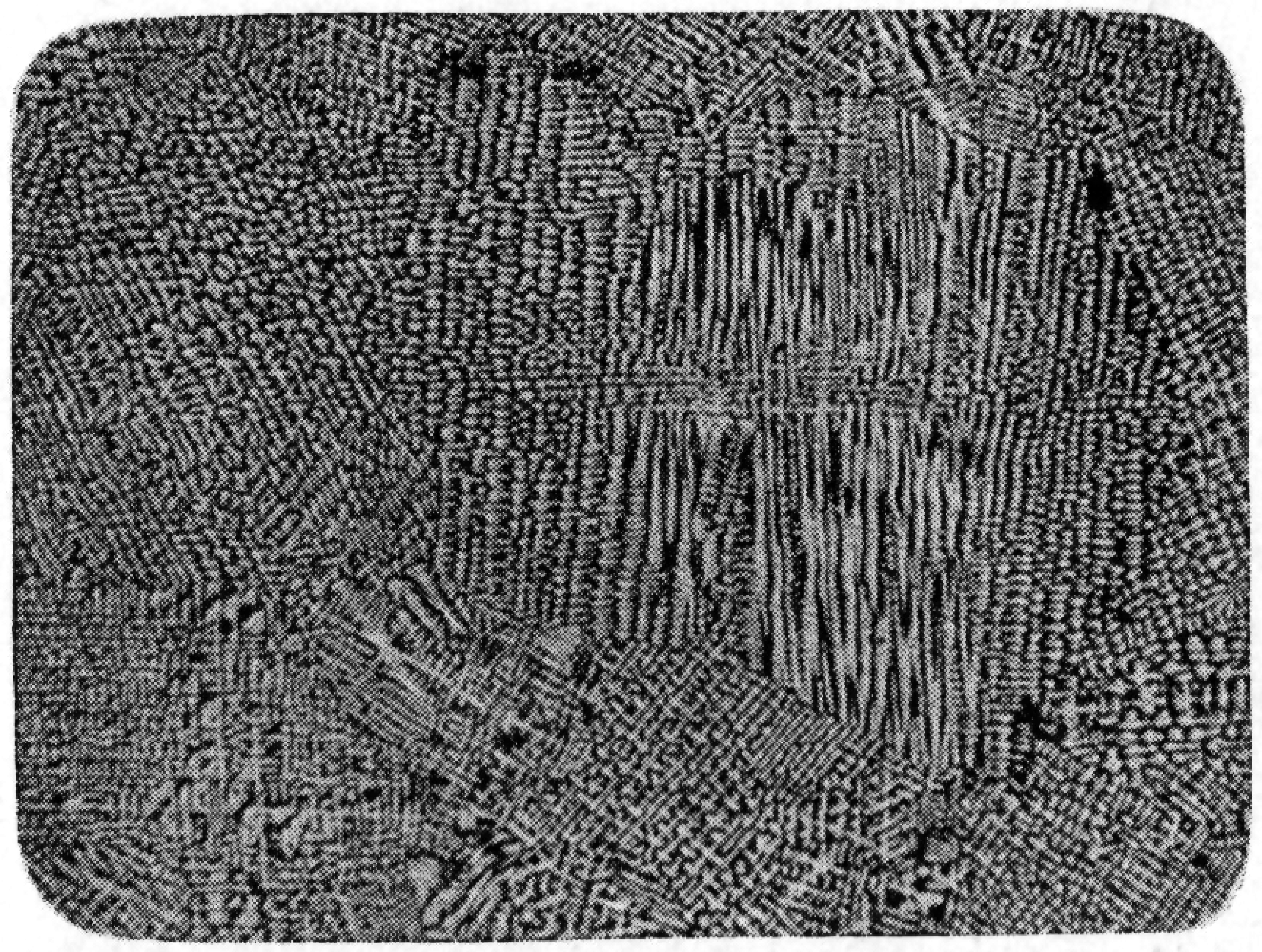

FIG. 2–4. Photomicrograph of alloy of 60 per cent gold and 40 per cent silver, showing heterogeneity or coring. Light-colored dendrites are rich in gold. ×100. (Courtesy of School of Mines and Metallurgy, University of Minnesota.)

As the temperature reaches T' the composition of the solid, which has precipitated out, is changed from *S* to S', while the composition of the remaining melt shown at L' consists of approximately 70 per cent of metal *A* and 30 per cent of metal *B*.

With a further reduction in temperature from T' to T'', the last traces of liquid of composition L'' solidify out. The composition of this last melt to freeze is about 82 per cent of *A* and 18 per cent of *B*.

Below temperature T'', this alloy is completely solid and, provided the cooling has proceeded under conditions approximating equilibrium, the alloy will have the same general appearance as a pure metal.

If a rapid cooling rate should prevail so that equilibrium could not exist, a condition known as coring results. In coring, the first crystal grains to solidify show a different structure from those which solidify later.

A cored structure is shown in Fig. 2–4. If heated to a temperature approaching but not exceeding the solidus and then cooled slowly, the metals will become thoroughly diffused in one another, and the structure appears as a homogeneous solid solution.

2–4. Metals Soluble in Liquid State but Insoluble in Solid State.

Metals mutually soluble in the liquid state and insoluble in the solid state must solidify distinctly and separately and form crystals representative of each metal. The cooling curve of such an alloy is shown in Fig. 2–5. As in the preceding examples, it is seen that the cooling of the alloy proceeds normally until point *a*, temperature *T*, is reached. At this temperature, the crystals formed are not composed of a solid solution of two metals but of pure *A*. With successively lower temperatures between *T* and T', crystals of pure metal *A* continue to separate out, while the composition of the melt becomes increasingly richer with respect to metal *B*. At T', the melt stable at that temperature solidifies, with the formation of crystals of both metal *A* and metal *B* constituting an aggregate or mixture of both metals in definite proportions. During the simultaneous precipitation of crystals of both metals at T', it is noted that the alloy cools at a constant temperature after the manner of pure metals. When solidification is completed, normal cooling again occurs. The constitution diagram of alloys of this type, with a series of cooling curves superimposed, is shown in Fig. 2–6.

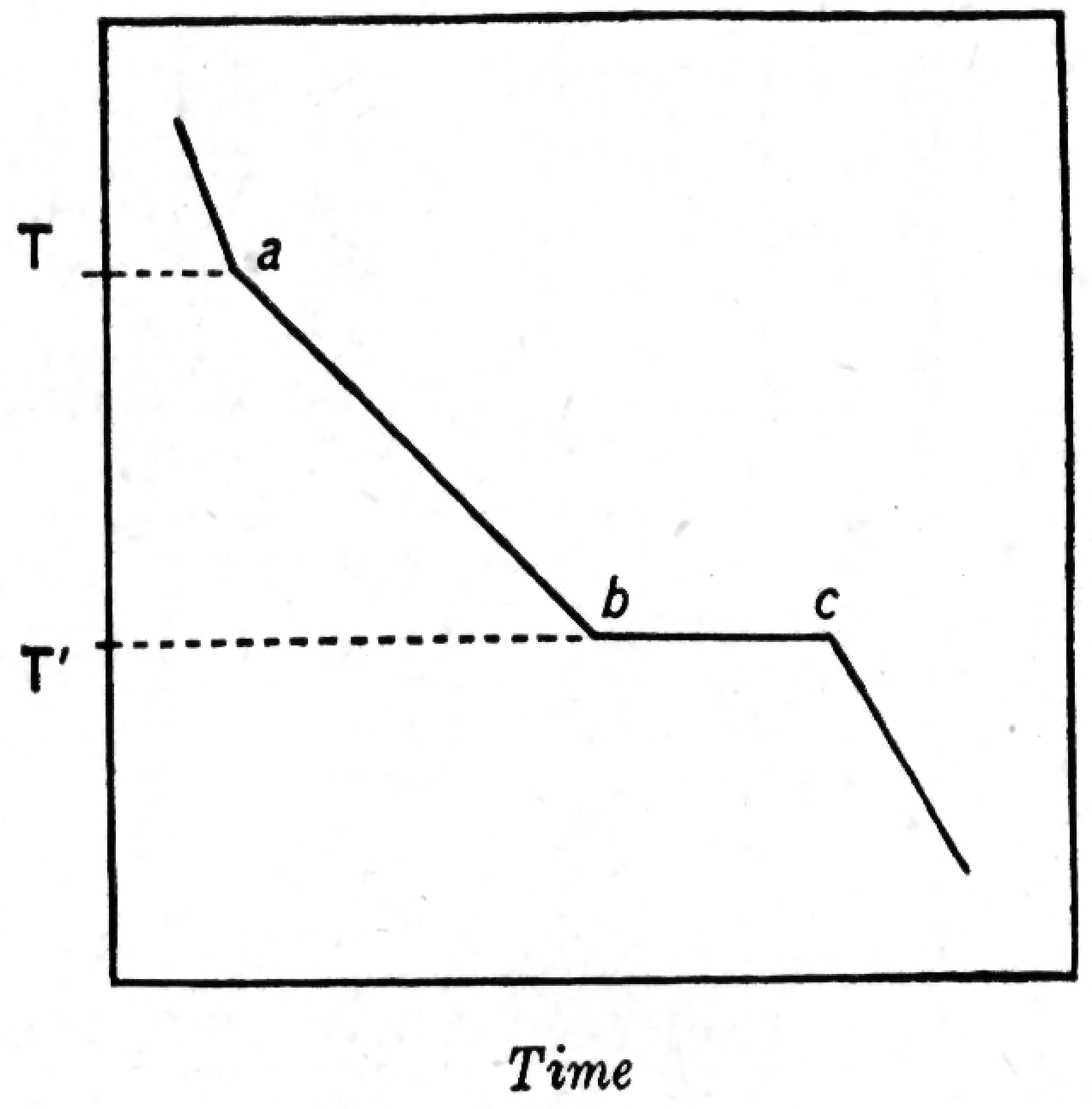

FIG. 2–5. Cooling curve of alloy of two metals, soluble in liquid state and insoluble in solid state.

The solidification of metals whose equilibrium diagrams conform to this type may be studied further by noting the influence of various amounts of sodium chloride on the freezing point of water and on the structural components at subfreezing temperatures.

By reference to Fig. 2–7, it is seen that the addition of 10 per cent of NaCl to water lowers its freezing point from 32 to 16F. At this temperature, pure water freezes, forming ice crystals. The separation of this solid (ice) results in an increased concentration of NaCl in the remaining brine. With this enrichment of the brine, further formation of ice can take place only as the solution reaches lower temperatures. Therefore, as the temperature of the solution falls further, the formation of ice crystals continues with a progressive increase in the concentration of salt along the curve (liquidus) *MO*. By the time the solution has reached −7.6F, the amount of salt in the residual brine has reached a value of 23.5 per cent. With the removal of the latent heat of fusion, the solution will freeze at this constant temperature after the manner of a pure substance, when both components of the system will precipitate simultaneously and form an intimate mixture of definite proportions of ice and salt crystals. This value of 23.5 per cent NaCl is known as the eutectic composition of NaCl and H_2O solutions. The temperatures at which solutions solidify in this manner and form eutectics are called *eutectic temperatures*.

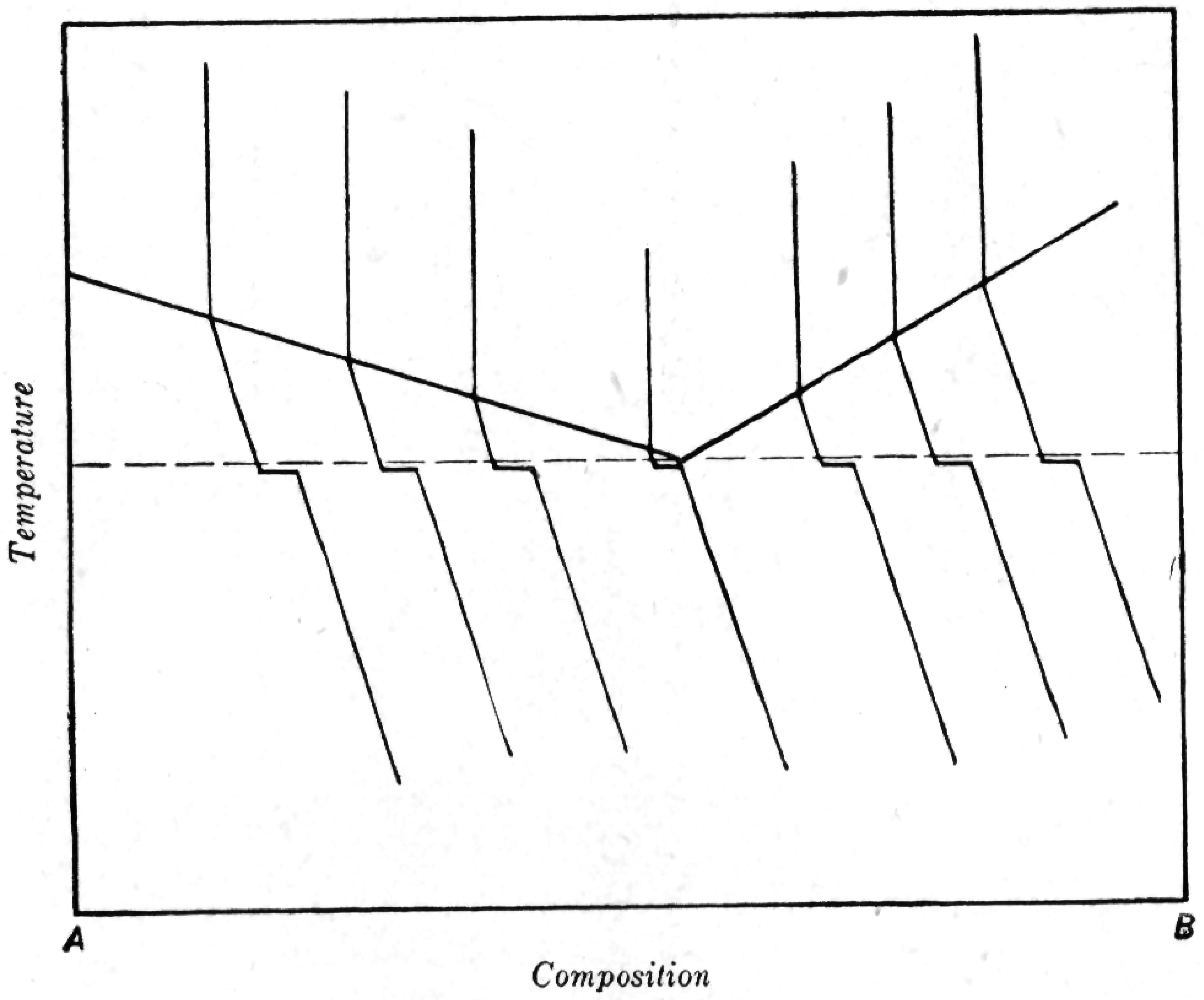

FIG. 2–6. Constitution diagram of binary alloy, components of which are soluble in liquid state but insoluble in solid state.

Below the eutectic temperature, normal cooling of the solid can again take place.

Solutions, in which the percentage of salt exceeds the eutectic ratio, freeze in the same fundamental manner as the example given of those containing less than this amount; i.e., they solidify selectively with a separation of one of the components until the eutectic composition is reached. With a solution containing 30 per cent salt, for example, crystals of salt will form and separate out at the temperature where the concentration vertical and the liquidus curve *OP* intersect. As the temperature falls to lower levels, precipitation of salt crystals continues until a temperature of −7.6F is reached, when the residual brine freezes as before.

As shown on the diagram, the solid components of a brine containing less than 23.5 per cent NaCl, or hypoeutectic solutions, will be ice and eutectic mixture; the solid components of a brine containing more than 23.5 per cent, or hypereutectic solutions, will be salt crystals plus eutectic.

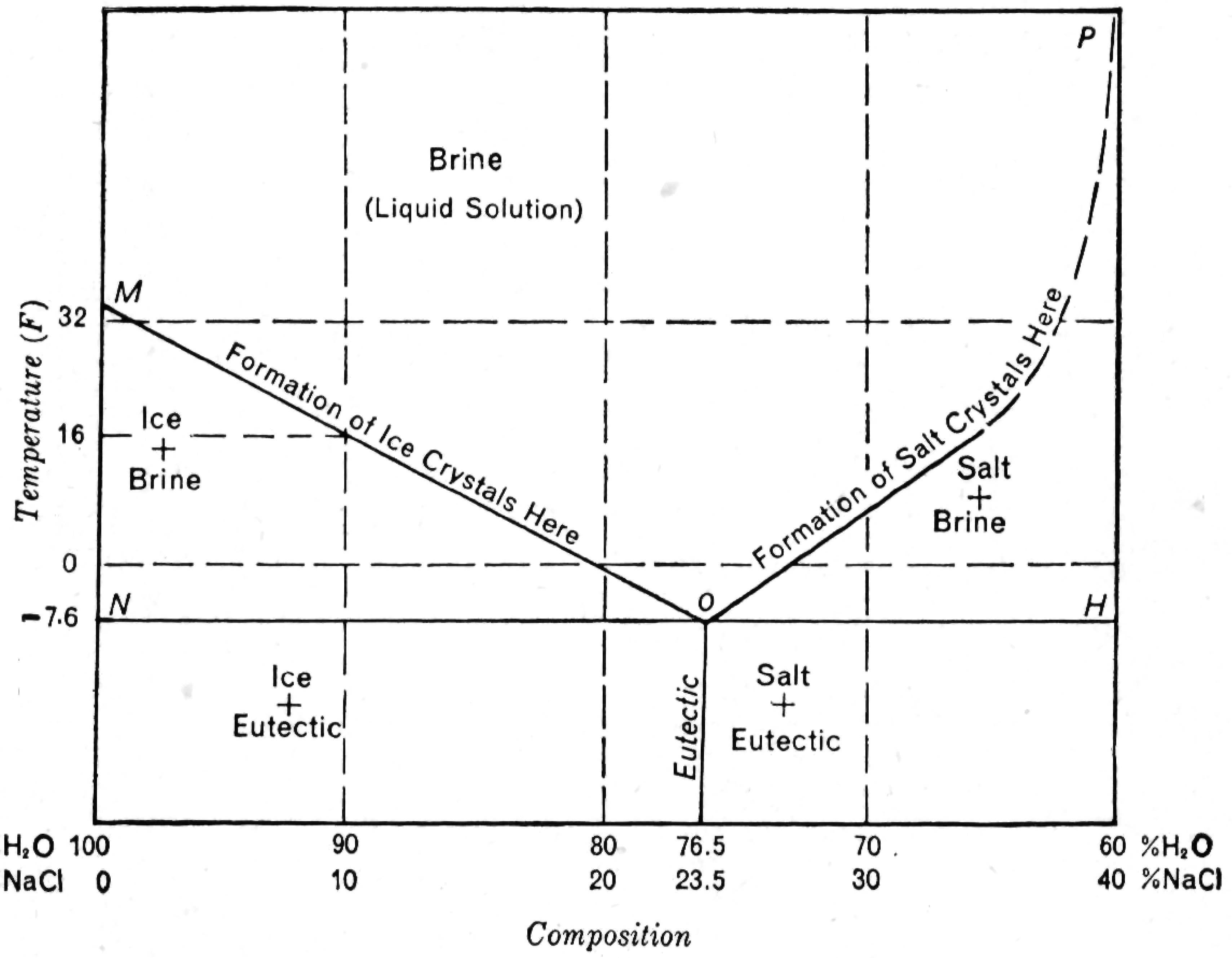

FIG. 2–7. Equilibrium diagram of H_2O-NaCl solutions.

Diagrams of this type are representative of binary alloys, the components of which are soluble in the liquid state but form mechanical mixtures or eutectics in the solid state. Common examples of this type are the constitution diagrams of cadmium-bismuth and thallium gold. The number of alloys in which the metals are completely insoluble in the solid state is small, although a considerable number approach this condition.

2–5. Metals Soluble in Liquid State and Only Partially Soluble in Solid State. Alloy systems, composed of metals soluble in the liquid state and only partially soluble in the solid state, solidify according to the diagram shown in Fig. 2–8. This type of diagram represents the most common classes of alloys, of which Cd-Zn, Ag-Cu, Cu-Al are examples.

If an alloy containing 80 per cent of *A* and 20 per cent of *B* is considered, the metals above the liquidus *MNC* constitute a single-phase liquid. At point *O*, temperature *T*, freezing of primary crystals begins, as in Fig. 2–7. The first liquid to freeze is not pure *A*, however, but has a composition denoted by point *S′*, which corresponds to approximately 95 per cent of *A* and 5 per cent of *B*. Therefore, instead of precipitating a single constituent, the crystallizing forces at that temperature are sufficiently strong to cause atoms of both metals to be incorporated in the space lattice of *A*. When the temperature drops to *T′*, more *B* atoms are included in the *A* lattice, as represented by *S″*.

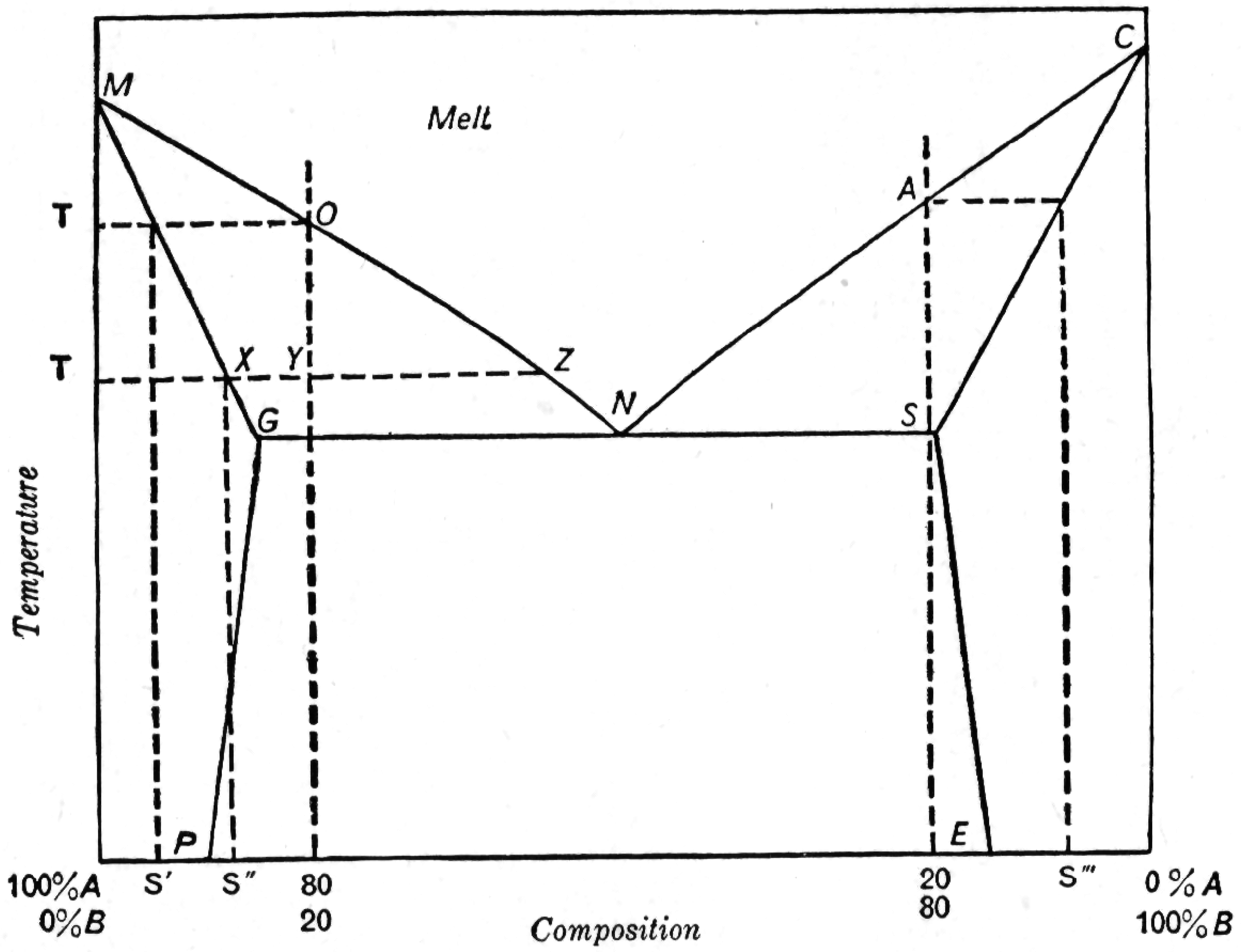

FIG. 2–8. Constitution diagram of alloys whose components are soluble in liquid state and partially soluble in solid state.

If an alloy composed of 20 per cent of *A* and 80 per cent of *B* is considered, a similar phenomenon exists since, at point *A* on curve *NC*, we would have the solution of metal *A* in metal *B*. The composition of the first melt to freeze is shown at *S‴*.

The diagram indicates that the solid solubility of *B* in *A* reaches a maximum at temperature *GNS*, while below that temperature the solubility decreases as shown by *GP*. On the right-hand side of the diagram, the solid solubility of *A* in *B* is also shown to reach its maximum at temperature *GNS* and decreases to room temperature as shown by *SE*.

2–6. Alloys Insoluble in Both Liquid and Solid State. The equilibrium diagram of a binary alloy system, consisting of metals which are completely insoluble in both liquid and solid state, is shown in Fig. 2–9.

Each metal solidifies at its proper temperature and is unaffected by the presence of the other. Each also crystallizes into its own space lattice and retains its own properties. For simplicity the constitution diagrams discussed represent binary alloys of various degrees of liquid and solid solubility and include some of the more fundamental reactions encountered during the cooling of the most important alloys. Many alloys remain to be studied whose constitution diagrams are quite complex.

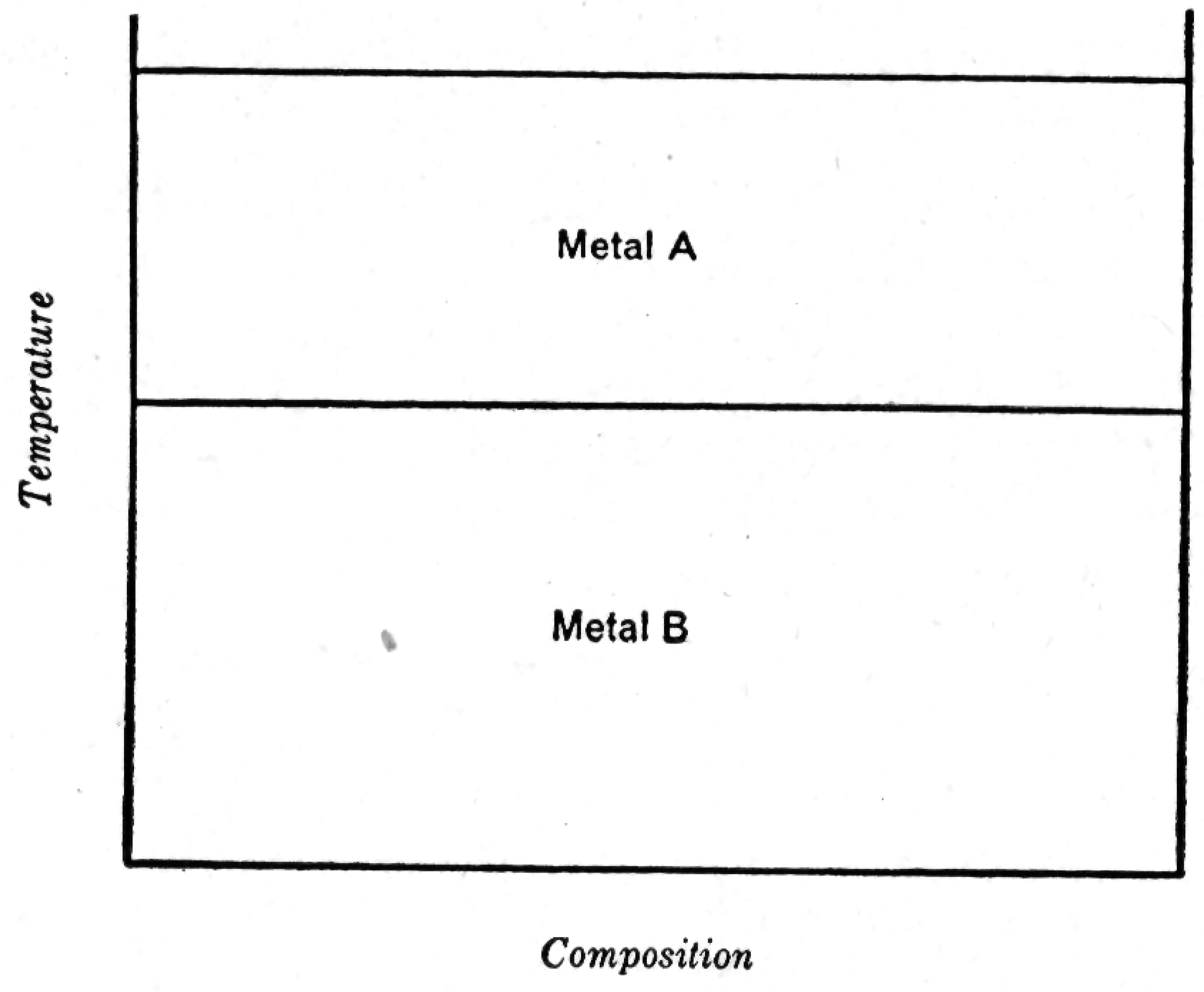

FIG. 2–9. Equilibrium diagram of two metals, completely insoluble in both liquid and solid states.

Because of its unique importance as a basis for the heat treatment of steels, the iron–iron carbide equilibrium diagram is described in Chapter 9.

2–7. Calculation of Phases. If the total concentration is known, it is possible to calculate from constitution diagrams the amounts of the various phases present and in equilibrium at any given temperature.

The method used is based on the relative inverse length of a lever-arm system, whose fulcrum is a point at which a total concentration vertical intersects a temperature horizontal that is projected through the field between the liquidus and solidus and extends from the concentration vertical to each phase. In Fig. 2–3, if we assume a total concentration represented by 50 per cent of *A* and 50 per cent of *B*, the percentage of solid in equilibrium with the melt at *T′* is equal to $\frac{M'O}{M'N'} \times 100$. The amount of the melt is equal to $\frac{ON'}{M'N'} \times 100$.

Similarly, we may calculate the percentages of the phases present at temperature *XYZ* in Fig. 2–8. The amount of the solid is equal to $\frac{YZ}{XZ} \times 100$, while the amount of melt is equal to $\frac{XY}{XZ} \times 100$.

It should be emphasized that the amounts are always in inverse ratio to the length of the lever arm. If the temperature horizontal $M'N'$, Fig. 2–3, is raised or lowered, it will approach zero where solidification begins or ends, respectively.

QUESTIONS AND PROBLEMS

1. Describe the conditions under which coring will take place and the mechanism by which a cored structure may be eliminated.
2. Give reasons for the difference in the forms of a time-temperature cooling curve of a pure metal and a solid solution alloy.
3. Define "eutectic" and "eutectoid."
4. Draw a constitution diagram of two metals, such as bismuth and cadmium, which are soluble in the liquid state and insoluble in the solid state. Name the phases and structural constituents at several temperatures. Assume various compositions below and above the eutectic composition, and analyze the changes which occur at various temperatures.
5. Draw a constitution diagram of a gold-silver alloy, and explain fully what occurs during slow cooling of an alloy of 60 per cent gold and 40 per cent silver, at temperatures lying between the freezing points of the two metals.
6. Calculate the amount of the structural constituents and phases present when the alloy reaches 1700, 1400, and 1100F.
7. Define "equilibrium," "liquidus," "solidus," and "critical temperatures."
8. How may data derived from a thermal analysis of a series of alloys be used to construct an equilibrium diagram?
9. Which of the following types of alloys form a eutectic when cooling under conditions approaching equilibrium: metals mutually soluble in the molten and solid state; metals completely soluble in the molten state and completely insoluble in the solid state; metals which are insoluble in both the molten and the solid state; metals which are mutually soluble in the molten state and partially soluble in the solid state?
10. Explain fully why pure H_2O and not brine freezes along *MS* in Fig. 2–3.
11. The homogeneity of the structure at normal temperatures of the gold-silver alloy after cooling slowly from the molten state is attributable to the mutual diffusion of the metal in the solid state. Give other examples of diffusion.

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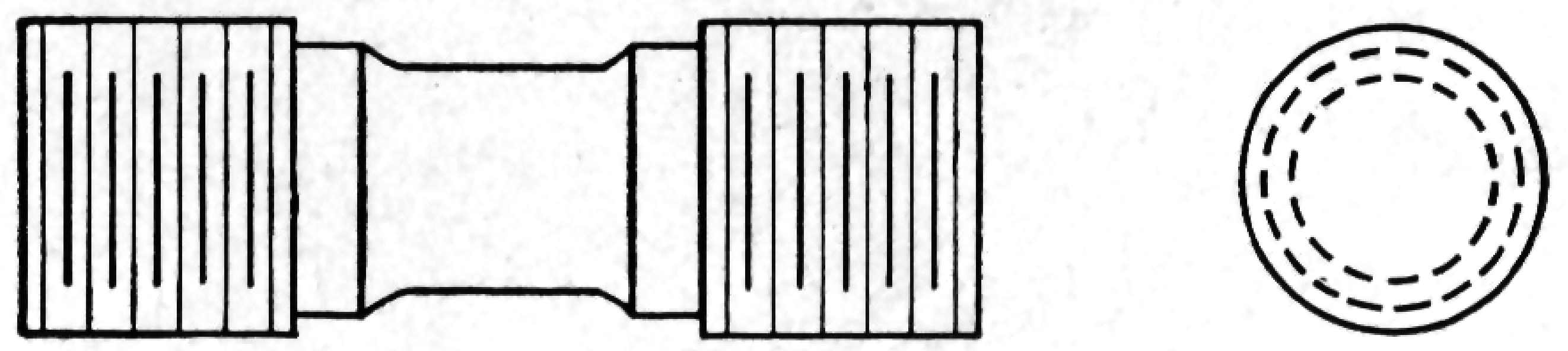
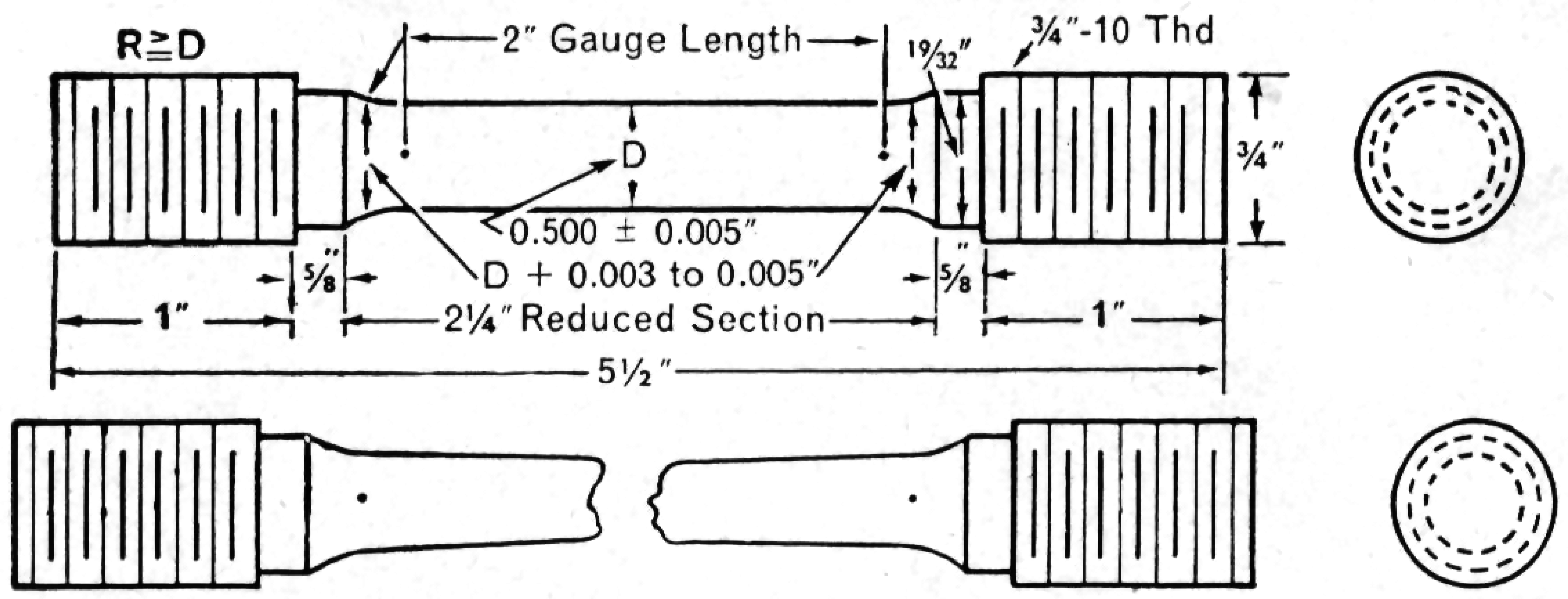
CHAPTER 3

PHYSICAL PROPERTIES OF METALS

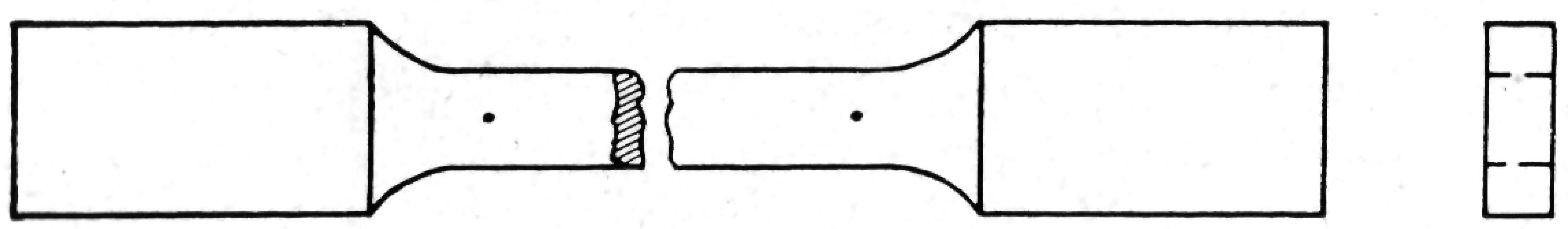
3–1. Introduction. The suitability of engineering materials for service may be determined by conducting various tests to obtain quantitative measurements of their performance under conditions paralleling their actual use as nearly as possible. Although the final acceptance test may be the performance of a part under operating conditions, extensive laboratory tests, when conducted scientifically and carefully, furnish a sound basis for selection and save both time and money.



(a) Cast-Iron Test Bar



(b) Tensile Test Specimen for Steels, Copper, Brass, Bronze, Etc



(c) Flat Test Bar Commonly Used to Test Strength of Welded Plates

FIG. 3–1. Tensile test specimens.

Chemical or physical tests or analyses may well be correlated with mechanical tests in the final selection of a material; ordinarily, however, satisfactory chemical tests are presumed when mechanical tests are applied. In some cases chemical analysis can determine broadly the type of material from which selection may be made, but the mechanical tests will make possible the selection of a *specific* material within the broader field.

3–2. Mechanical Properties. The behavior of a metal subjected to a stress is determined by what are broadly called its mechanical properties. The external forces to which a material is subjected are called *loads*. The resistance exerted by the body to the external loads is called internal force or *stress*. Changes in shape or size, produced by external forces, are called *deformations* or *strains*.

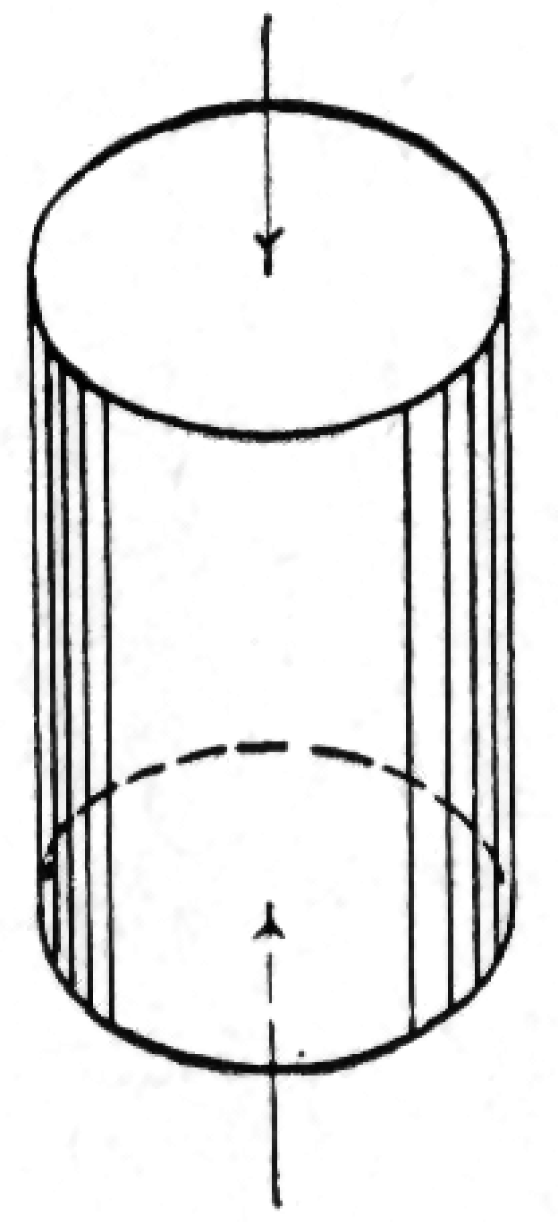


FIG. 3–2. Compression test specimen.

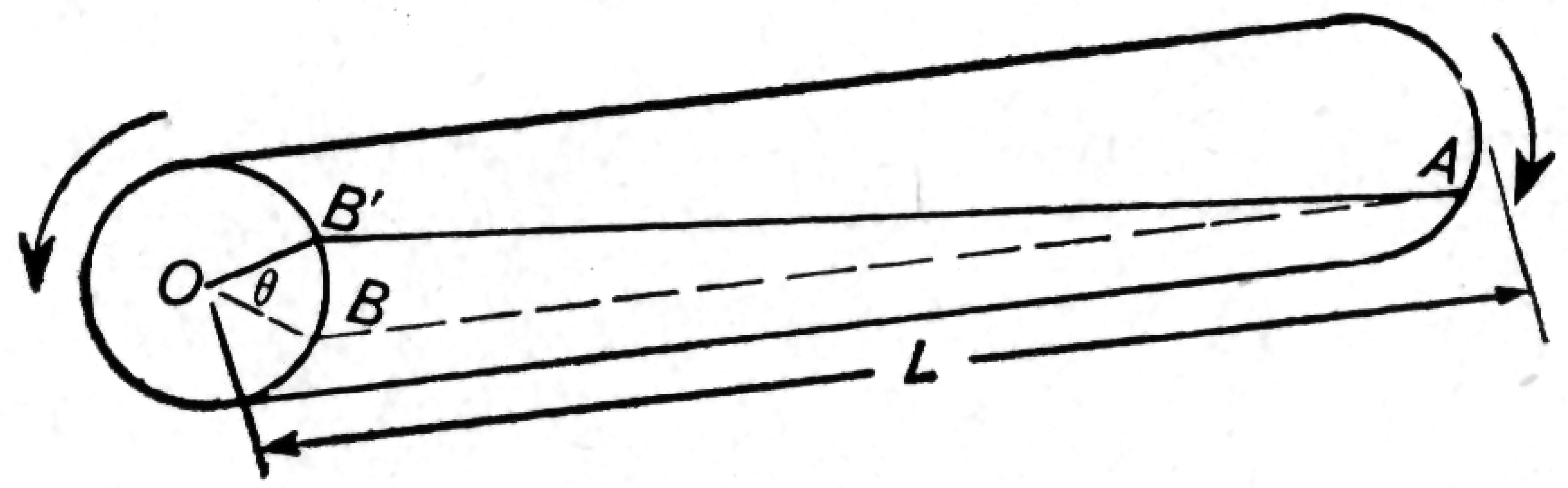


FIG. 3–3. Deformation in cylindrical bar after it has been subjected to torsion load. Line AB is an element of the unloaded shaft and OB the radius. When torque is applied, AB takes position AB' and OB rotates to OB' through the angle θ; θ is the angle of twist. BB' is the shearing deformation for the length L.

Stresses are identified as *normal* when the external force is perpendicular to the resisting area, such as when a tensile or a compression load is applied to the body. When the force is tangent to the area, it is called a *shearing stress*. Where stress is uniformly distributed, its intensity is equal to the total force, divided by the total area over which it is applied. The common units used for the expression of both normal and shearing stresses are pounds per square inch (abbreviated, psi).

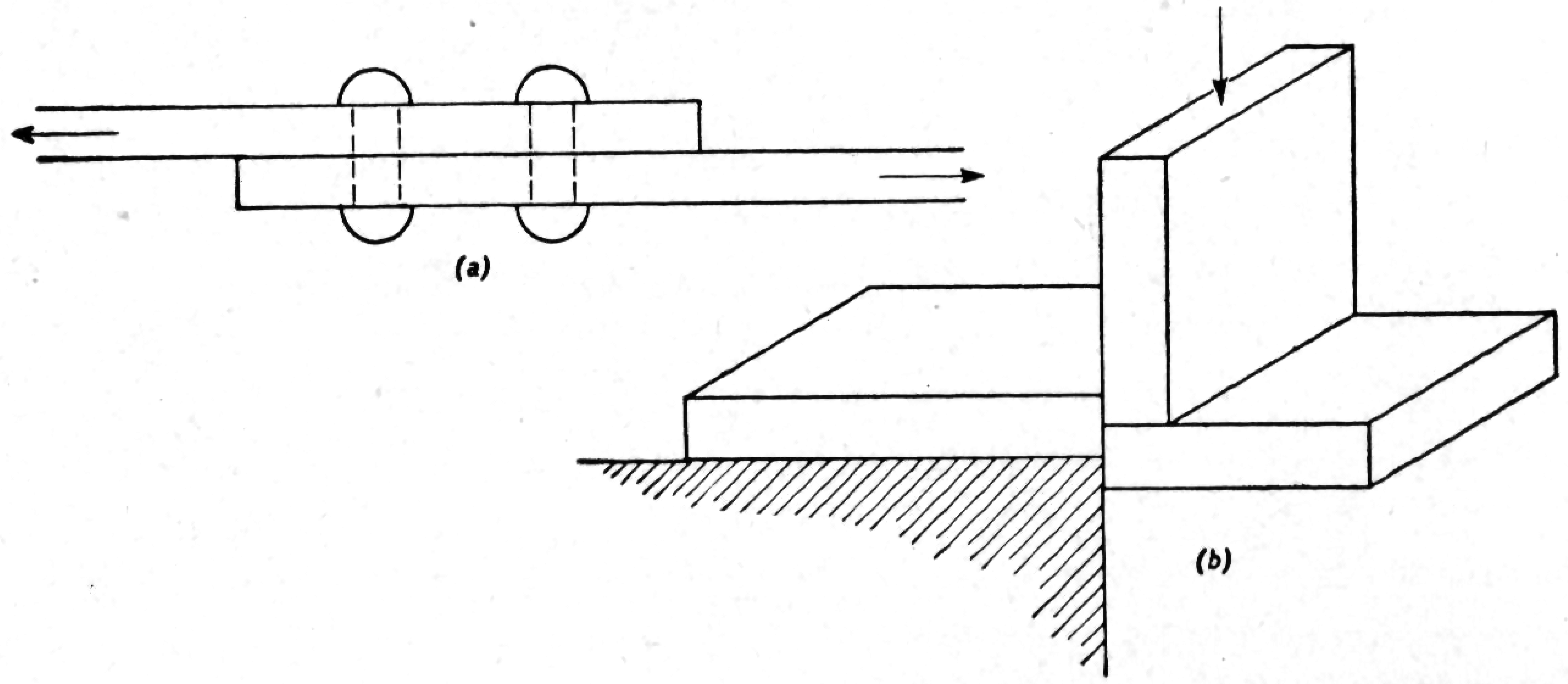


FIG. 3–4. Examples of shearing loads.

External forces in their application to material bodies are also classified with respect to direction and application. A load, acting along the axis of a test specimen, is called an axial load and may be a tensile or a compressive load. Test specimens for tension and compression are illustrated in Figs. 3–1 and 3–2. Loads which tend to twist materials are called torsion loads. A round shaft displaying angle of twist after torque has been applied is shown in Fig. 3–3. Shearing loads tend to cut the material across its area, as shown in Fig. 3–4 where the rivets at (*a*) are said to be in shear and where at (*b*) the plate is shown as having been sheared by a force applied transversely to its surface.

With respect to the manner of applications of loads, forces are classified as (1) static, in which a body is subjected to a slowly applied or constant load; (2) impact, or dynamic, where a load is suddenly applied as by a blow; (3) repetitive, or cyclic, in which the body is subjected to a large number of repetitive loads.

Other tests determine hardness or resistance to penetration, resistance to abrasive wear or to corrosion under various chemical and industrial conditions, creep or dimensional changes under load, and oxidation at elevated temperatures.

In this chapter a few of the most common of the mechanical tests will be discussed. These include the tensile, fatigue, impact, torsion, shear, transverse, compressive, creep, damping, and hardness tests.

3–3. Tensile Testing. Certain properties of metals are most commonly and economically investigated by the tensile test, for which a carefully prepared sample test bar, representative of the material being studied, is subjected to an increasing application of axial load until its failure occurs. Round and flat tensile test specimens are shown in Fig. 3–1. One standard test specimen of the type shown in Fig. 3–1 at (*b*) is a round bar 0.505 in. in diameter and corresponding to an area of 0.2 sq in. It is machined accurately and is free from circumferential scratches, indentations, or ridges. It is threaded on both ends so it can be secured in the testing machine. Before its attachment to the testing equipment, the bar is marked with two small center punch marks, 2 in. apart, to designate the *gauge* length. When securely attached, the specimen is subjected to a uniformly increasing load until its ultimate strength or the maximum unit stress, based on the original cross-section area, is determined. All data relative to its properties are based on its behavior in the section between the gauge marks or reference area. The unit stress in psi for any value P pounds, shown on a graduated loading beam or dial, corresponds to P/A, where A equals the cross-section area of the specimen in sq in.

Testing machines are operated either hydraulically or mechanically, and many types of machines are adapted for testing materials in tension, compression, and bending. When properly calibrated, these machines give readings with a limit of error of less than one per cent. If the speed of testing becomes excessive, the test results are affected markedly in certain materials. In general, the rate of strain should be kept low enough to permit the taking of load and deformation readings during the test. Some standards (for instance, ASTM designation E9-33T on compression testing) specify maximum permissible testing speed. Two types of testing machines are shown in Figs. 3–5 and 3–6.

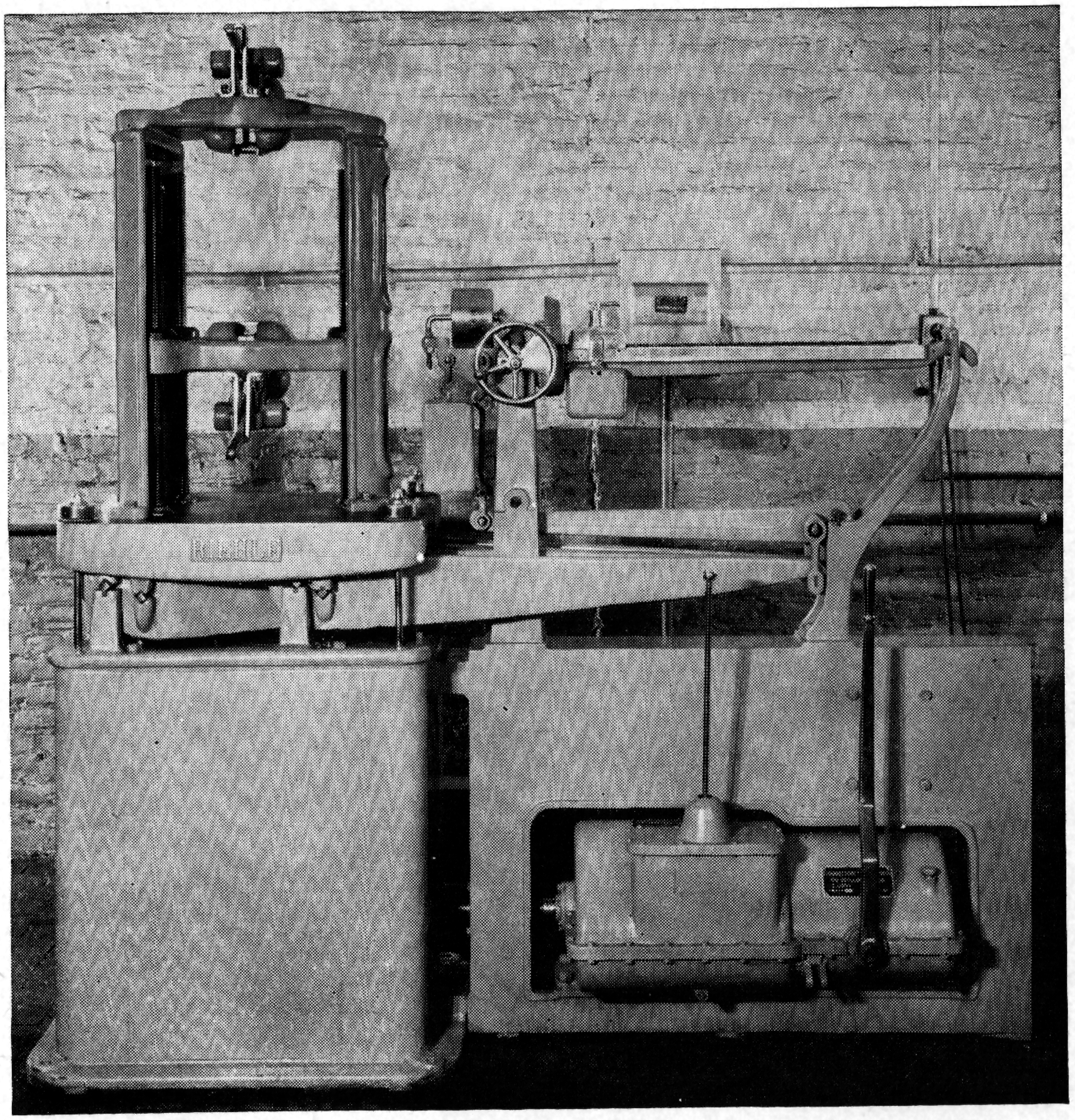


FIG. 3–5. A 50,000-lb. standard universal testing machine. (Courtesy of American Machine and Metals Inc., East Moline, Ill.)

The purpose of the tensile test is to determine (1) the maximum unit tensile stress of the material; (2) the yield strength of ductile metals; (3) the amount of increase in length or elongation, called *strain;* and (4) the decrease in the diameter or area of the specimen, called *reduction of area.* The percentages of elongation and of reduction of area, computed on the basis of the original dimensions, express the *ductility* of the material.

By means of an instrument called an extensometer, accurate measurements of changes in gauge length, made after the test is begun, will indicate that the unit strain and the unit stress increase in the same ratio. This phenomenon, known as Hooke's Law, applies as long as the unit stress does not exceed a certain value known as the *proportional limit.* If continued beyond this value, the tensile loading of ductile metals will produce plastic flow or deformation when the unit strain increases at a greater rate than the unit stress. This is shown by point *C* in Fig. 3–7. This unit stress is known as the *elastic limit.* Though they are not exactly identical, the proportional and elastic limits are usually considered equal for practical reasons. Should the load be removed at a unit stress that is below the proportional elastic limit, the metal will return to the original gauge length. If, however, the unit stress exceeds the elastic limit of the metal before being removed, the specimen assumes a permanent "set" and will not return to its original length. Within this limit of stress, metals exhibit a complete elastic recovery.

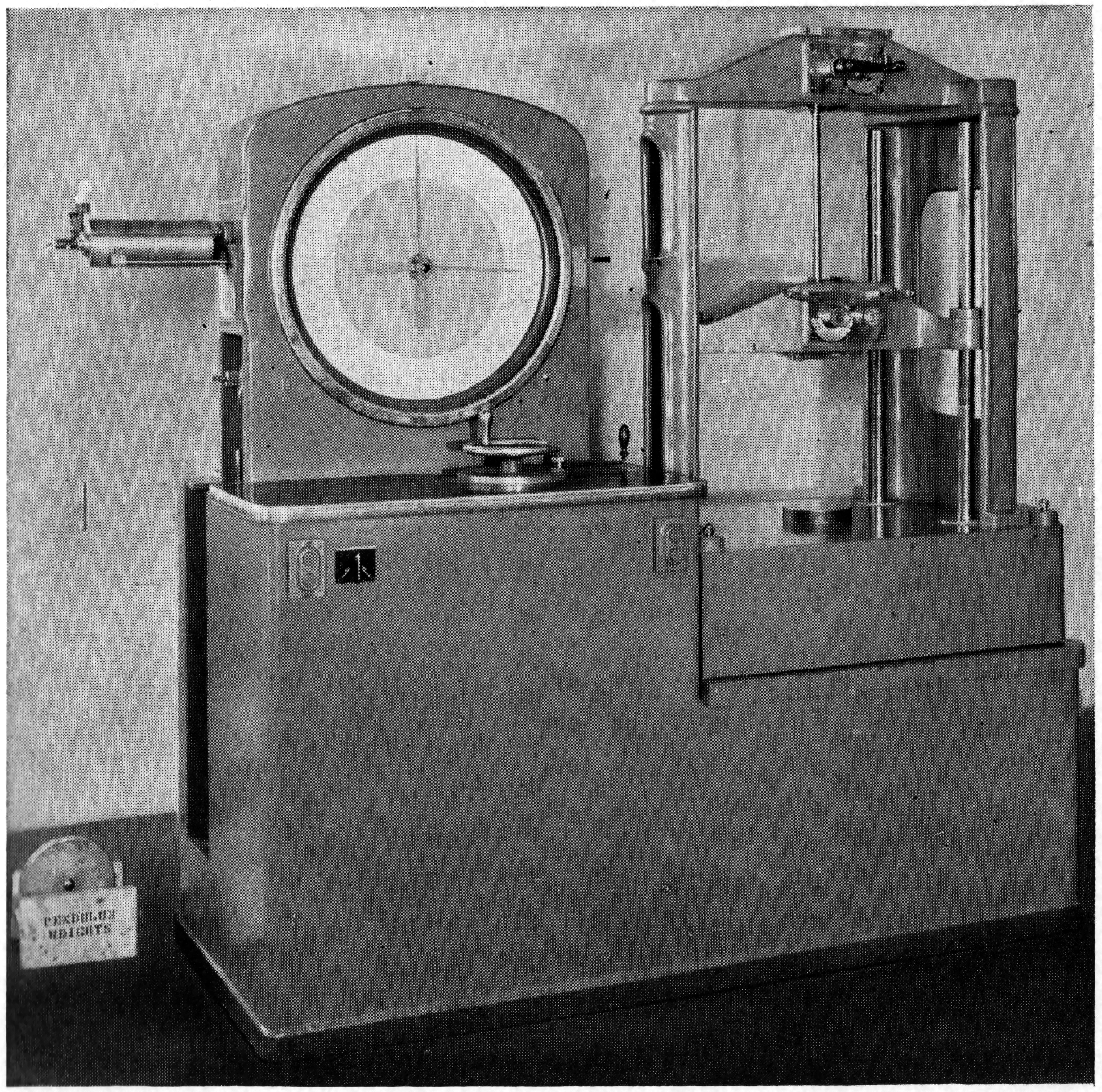


FIG. 3–6. Hydraulic recording, tensile testing machine. (Courtesy of American Machine and Metals Inc., East Moline, Ill.)

The unit stress at which ductile metals continue to elongate with only a slight increase in the applied load is called the *yield point.* It is defined as the unit stress at which there occurs a marked increase in strain without an increase in stress. It is shown in Fig. 3–7 as the sharp knee or abrupt change in the slope of the curve at D.

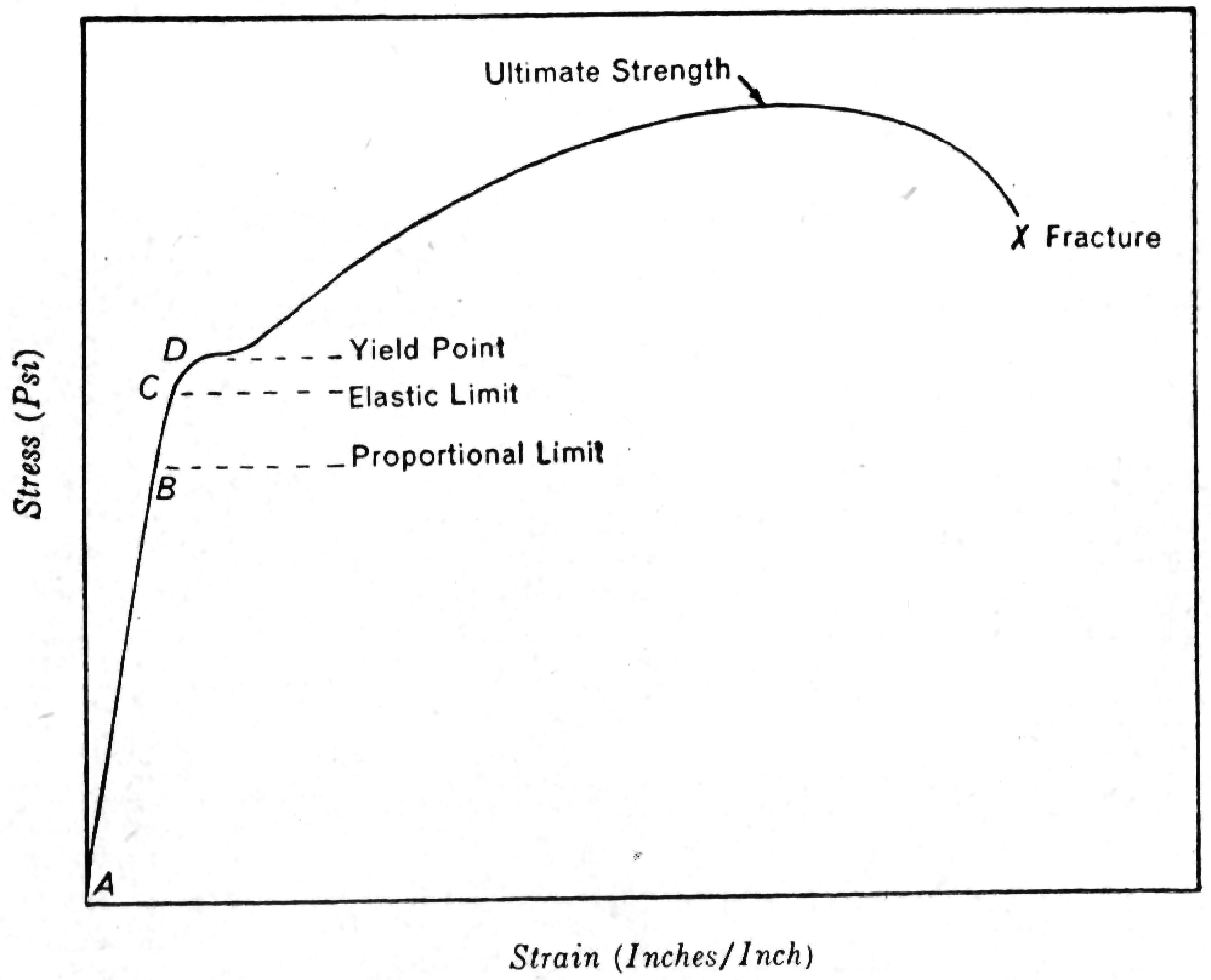


FIG. 3–7. Stress-strain diagram for low-carbon steel, copper, aluminum, and similar ductile metals.

In order that members of machines and structures can fulfill their proper functions, the maximum allowable working stress must be less than the proportional elastic limit. For ductile metals the working stress is usually considerably *less* than the elastic limit of the materials.

The stress-strain relation of certain brittle metals such as gray cast-iron, which possesses only limited or zero ductility, is shown in Fig. 3–8. It is characterized by a practically uniform curve, and a yield point is not indicated.

After a ductile specimen reaches its ultimate unit strength, a gradual local constriction or "necking down" will take place, which reduces the effective resisting stress area so that the load, required to cause continued elongation of the bar, decreases as shown in Fig. 3–7. Although the true value of the stress required to break the specimen is the breaking load divided by the unit area at the reduced section, the ultimate strength is generally computed by dividing the maximum load by the original cross-section area.

After the specimen is broken and removed from the machine, the ends are placed tightly together, and measurements are taken of the increase

in length or elongation and of the reduction of area at the neck. These values are expressed as percentages of the original dimensions.

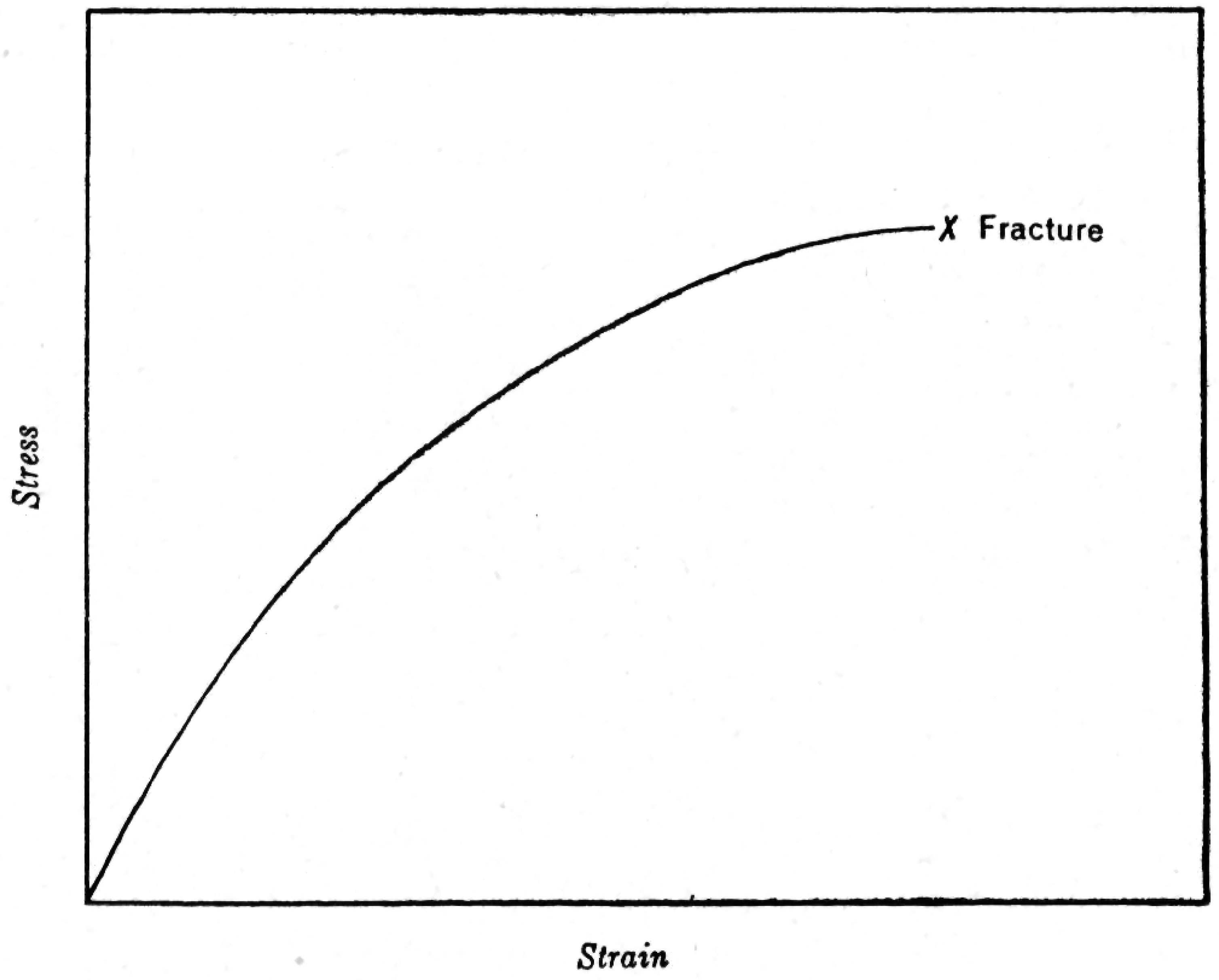


FIG. 3–8. Stress-strain diagram for cast-iron and similar brittle materials.

As is shown in succeeding chapters, the tensile and other properties of some metals and alloys are greatly influenced by various forms of heat treatment and mechanical work.

3–4. Fatigue Test. The design and material suitable for a part required to perform under a variable and repeated stress cannot be determined solely on the basis of the behavior of a material under static forces or under a condition of constant loading. For example, in service a coil or flat leaf spring is subjected continuously to alternating stresses of variable magnitude, a condition for which a tensile test result would be an inadequate criterion in selecting suitable material. For such conditions a more suitable test is a fatigue test, in which a representative specimen is subjected to a sufficient number of stress applications of known intensity.

In its application to metals, the term "fatigue" is largely misleading and confusing, since failure of parts under such a test is effected in a progressive sequence beginning with a flaw, inclusion, scratch, or a sharply reduced cross-section that acts as a stress raiser or stress concentration zone. From such areas under repeated stress, cracks develop and are propagated until eventually failure is caused through a greatly reduced effective area. If applied a sufficient number of times, a stress will cause rupture or failure in a part at a value far below the ultimate static strength of the material. The number of repetitions of stress necessary to produce failure depends on the maximum initial stress imposed, on the subsequent range of stress, and, particularly, on the design and surface finish of the part in the reference area. The maximum stress a specimen withstands for approximately 10,000,000 cycles without failure is called the *endurance limit;* and it has been found that, when a part does not fail when subjected to this number of maximum alternating stress cycles, it will in all probability not fail when stressed an infinite number of cycles. The endurance limit for a number of materials is shown in Fig. 3–9, which is known as the S–N diagram, where the stress and the number of cycles are plotted on a logarithmic scale. One type of fatigue specimen and testing equipment is shown in Fig. 3–10.

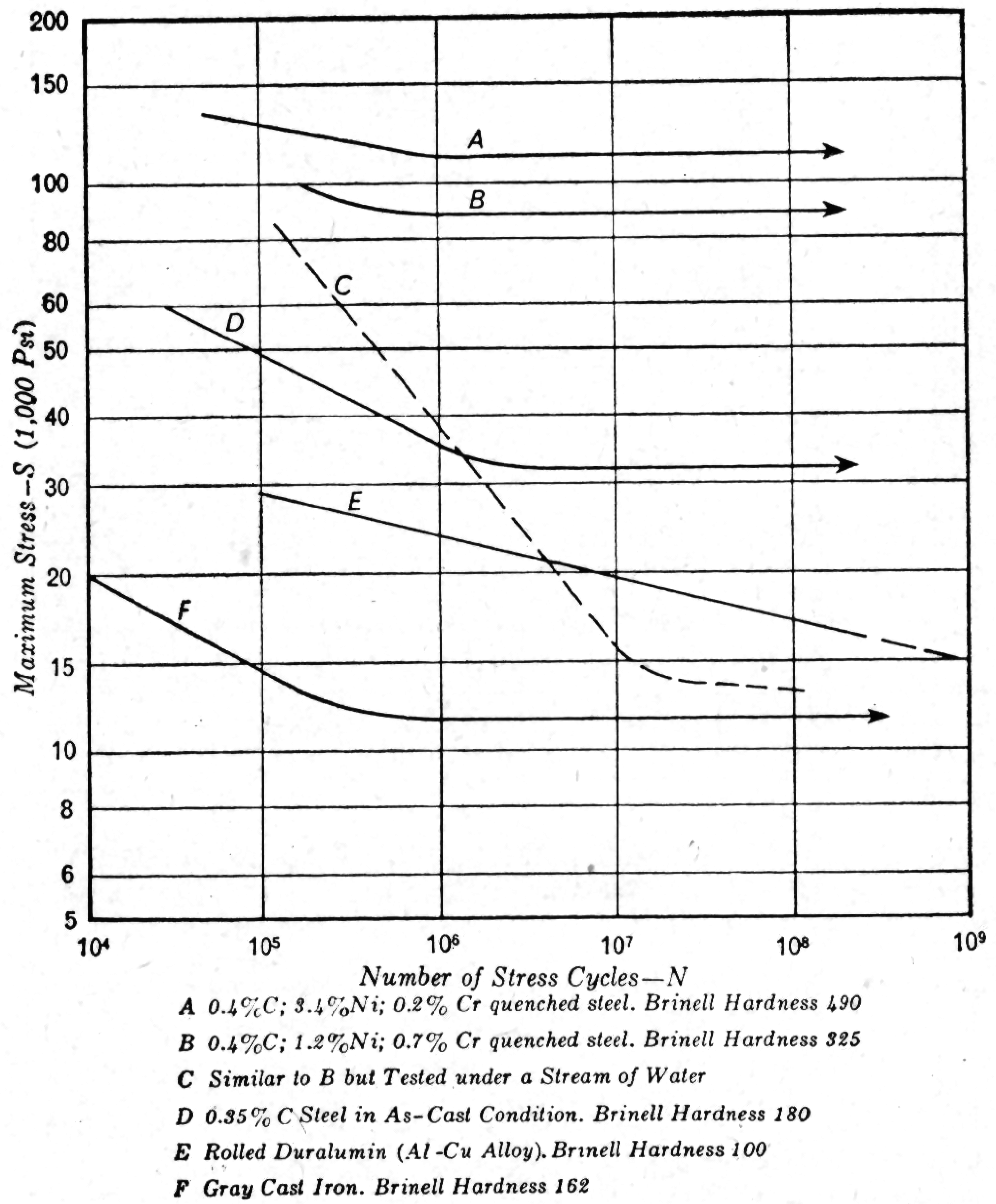


FIG. 3–9. *S–N* curves for some common metals. (Adapted from *The Fatigue of Metals* by H. F. Moore and J. B. Kommers.)

Failure of such parts as crankshafts, railroad car axles, automobile axles, springs, etc., is often ascribed erroneously by laymen to crystallization. Fatigue failures generally show a rubbed area centering around the point of instigation of the crack. When the crack has spread sufficiently, the remainder of the cross-section fails suddenly. The surface of the last fraction to break is unrubbed and appears coarser. It is from this coarser appearance that the misnomer of crystallization arose.

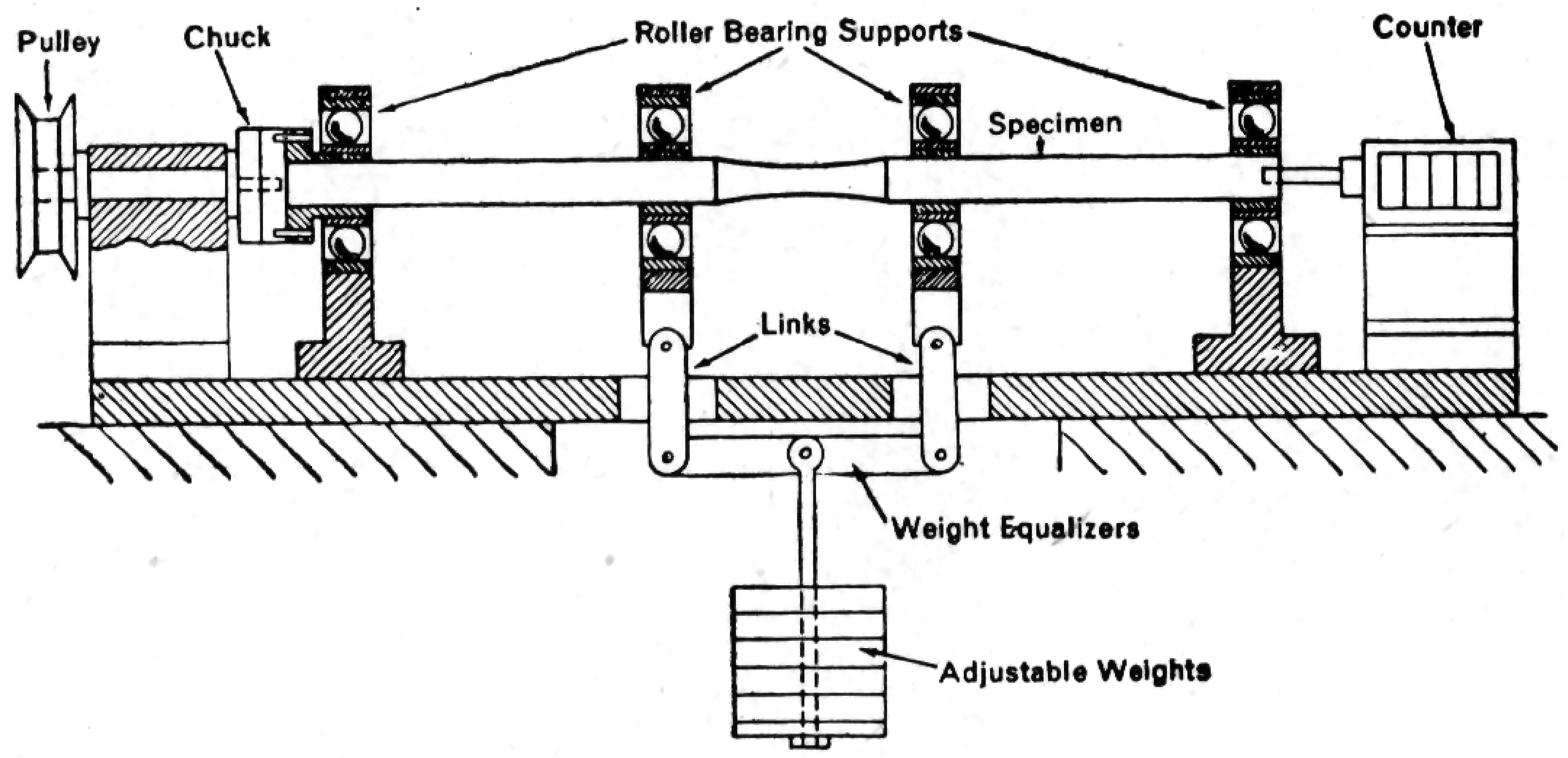


FIG. 3–10. Rotating, simple-beam type of fatigue specimen set up for testing.

Failure caused by repetitive stresses occurs across the grains or is transcrystalline and follows crystallographic planes.

3–5. Corrosion Fatigue. When a metal is subjected to a stress applied repeatedly under conditions favorable to mild corrosion, the endurance limit is lowered, although the loss of metal by corrosive action may be negligible. Ordinary commercial steels appear to possess no corrosion fatigue limit; and, given sufficient time, failure will occur at very low stresses. The main effect of the corrosion is to produce sharp pits, from which numerous cracks form, frequently meeting to form a serrated fracture.

3–6. Impact Test. The susceptibility of parts to failure under suddenly applied or dynamic stresses is investigated by means of laboratory tests called impact tests, the principle of which is based on the energy absorption of the material when ruptured by a falling mass. For qualitative comparisons, this energy is measured under controlled conditions. Types of specimens most frequently used are shown in Fig. 3–11. Fracture is caused through the notched or reduced section by a single blow, delivered by a pendulum consisting of a rigid rod and a heavy disk or hammer. The energy required in breaking the specimen is calculated from the angle generated by the pendulum, as indicated by the movement of a friction pointer over a scale graduated in degrees. The energy is expressed in meter-kilograms or foot-pounds.

Impact testing is conducted most commonly by means of the Charpy and Izod machines. In the Charpy machine, the test specimen, shown in

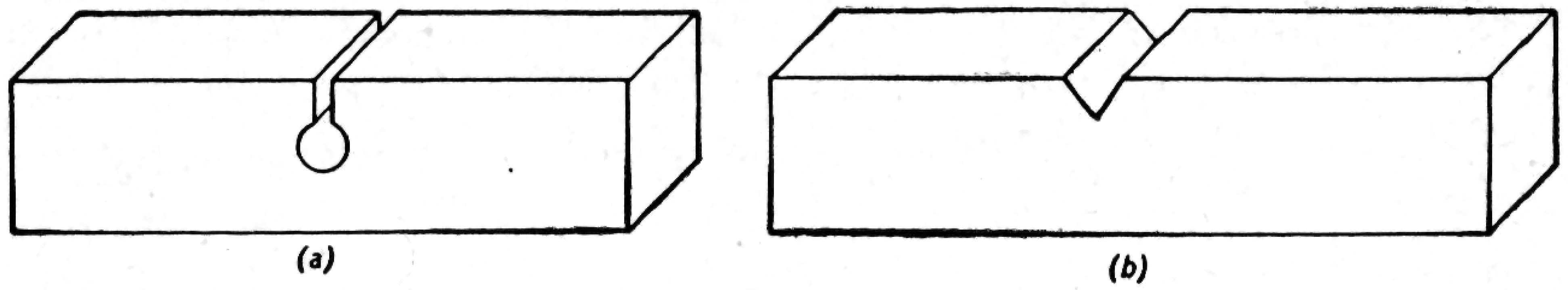


FIG. 3–11. Two types of impact test specimens. At (*a*), Charpy keyhole specimen; and at (*b*), Izod notched specimen.

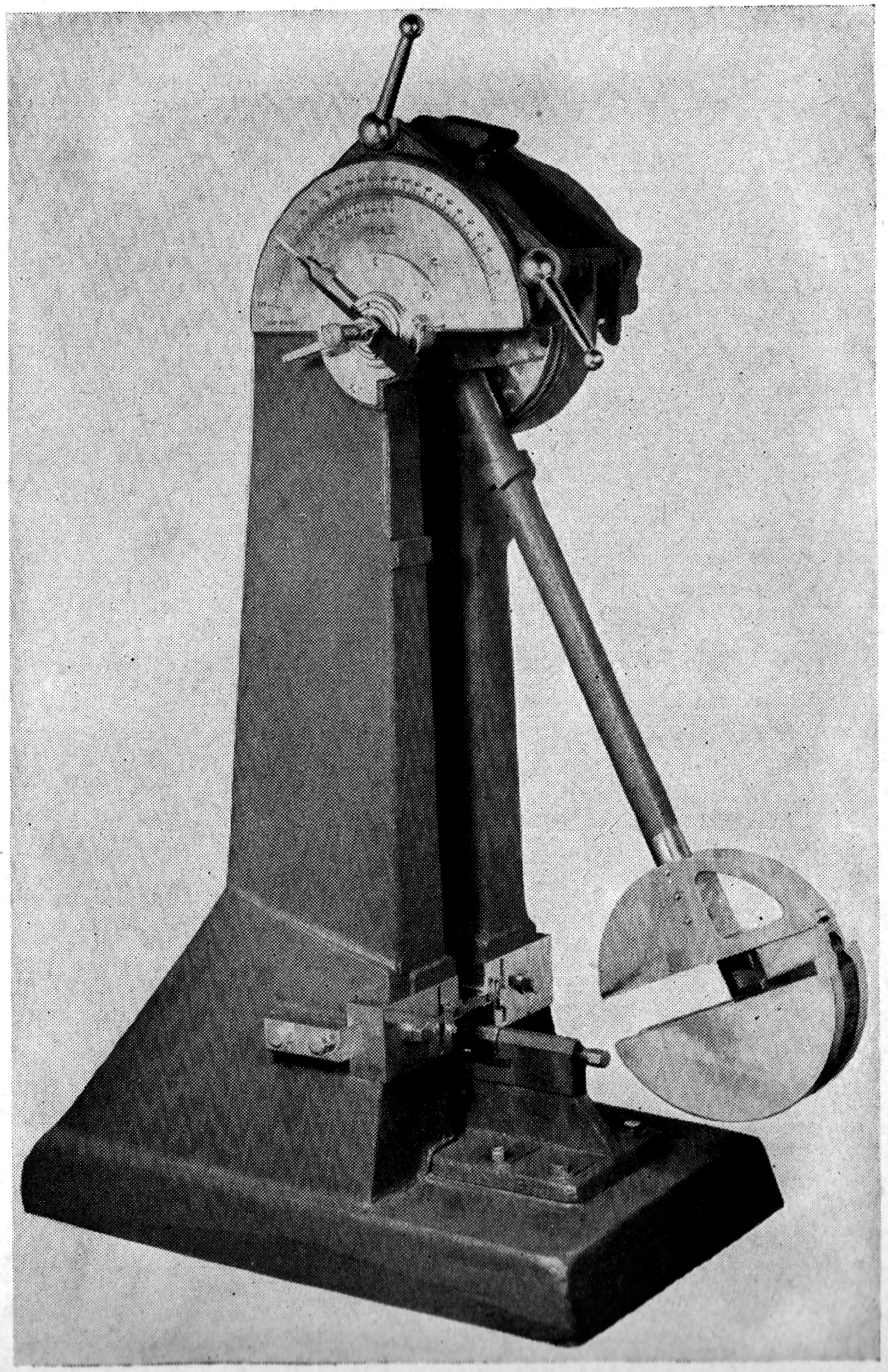


FIG. 3–12. Combination Charpy-Izod impact testing machine. (Courtesy of American Machine and Metals Inc., East Moline, Ill.)

Fig. 3–11 at (*a*), is placed as a simple beam on two supports and is struck opposite the notch at the midspan, as shown in Fig. 3–12. In the Izod machine the specimen, shown in Fig. 3–11 at (*b*), is tested as a vertical cantilever.

Impact values have little correlation with other physical properties of the metals but furnish a qualitative basis for selection when identically similar specimens are tested in the same way.

Little agreement prevails among engineers relative to the efficacy of the impact test in evaluating the resistance of metals to impact or shock loads, because parts in service are very seldom subjected to such drastic loading conditions. The test does emphasize the need for careful avoidance of notches in designing parts, since variations in the proportions or shape of the notch have significant influence on the impact strength. It also emphasizes the sensitivity of metals to notch or local stress concentration, in that the impact strength does not increase in proportion to section area.

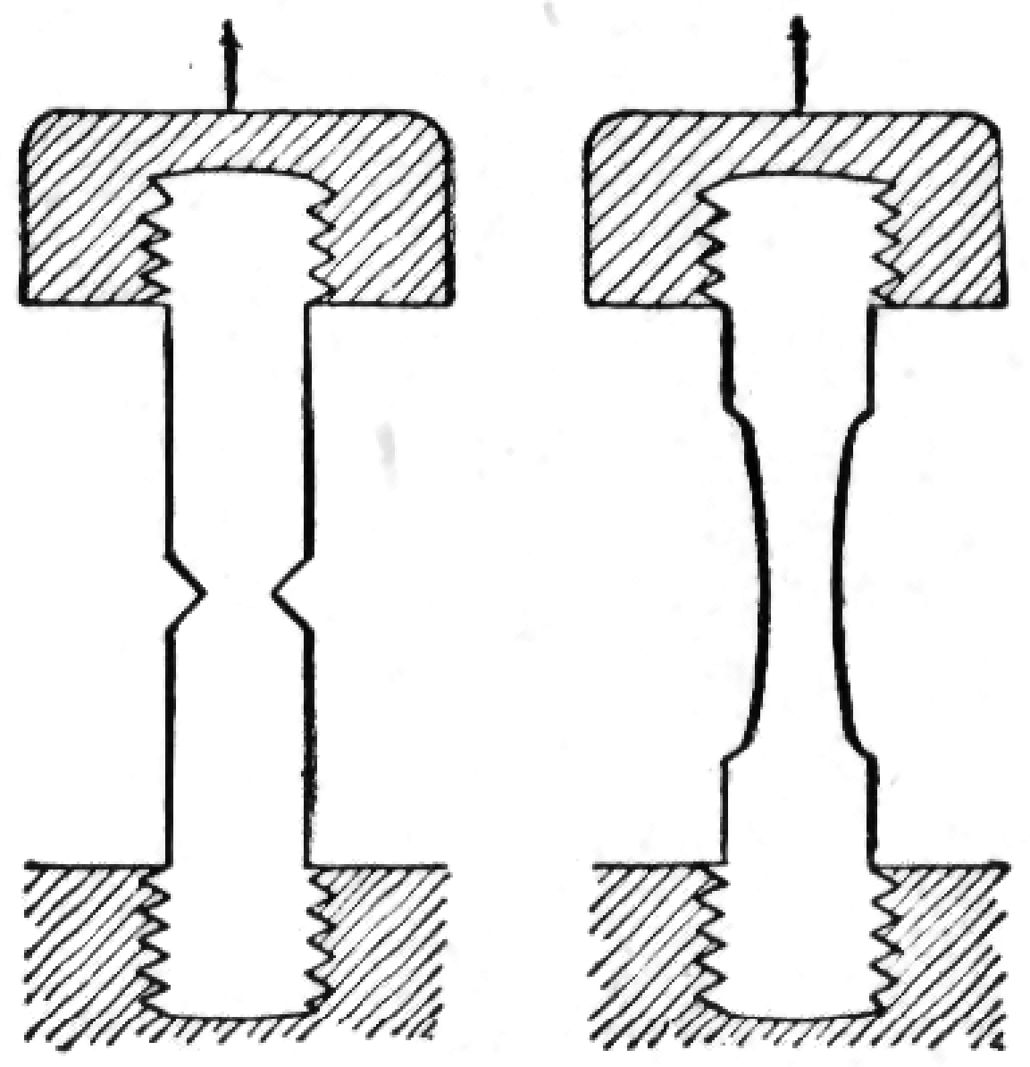


FIG. 3–13. Types of tension-impact test specimens.

However, the test is quite widely used, because it furnishes a qualitative basis for evaluating the effects of heat treatments (particularly changes in grain size) or for determining the relation between the temperature of the test piece (especially low temperature) and the toughness of the metal.

In view of the difficulty of obtaining reproducible results with the notched bar specimens, considerable possibility of improvement is anticipated from a combination tensile-impact test which has recently been developed. For this, test specimens shown in Fig. 3–13 are used. The test piece is secured to the back of a pendulum, which, as it falls, causes a hammer block attached to the outstanding end of the specimen to strike against two hardened anvils; and the specimen is broken in tension under a rapidly applied stress, as the pendulum passes the anvils.

3–7. Torsion Test. The energy resistance of metals in shear is investigated by the torsion test (Fig. 3–3); a bar attached securely in suitable chucks is subjected to a twisting force in a plane at right angles to its central axis. This force produces shearing stresses on each normal section of the shaft. The twisting moment, or stress load, in the bar is measured by instruments, from which data the maximum shearing stress is computed and stress-strain curves are developed. There is no reduction in area or elongation in the torsion test. Ductile materials break in a plane perpendicular to the axis, while brittle materials break along a helical surface. Shear strength varies in direct proportion to the tensile and yield strength of ductile materials. The shear strength of cast-iron varies from 1 to 1½ times the tensile strength.

Torsional stresses are exemplified in service by such parts as power transmission shafts, crankshafts, and propeller shafts.

3–8. Transverse Test. Gray cast-iron is usually judged by the results of a transverse test, in which the load is applied perpendicular to the longitudinal axis of the bar, as shown in Fig. 3–14. The test is normally performed on unmachined round bars and is used widely for foundry control and specifications.

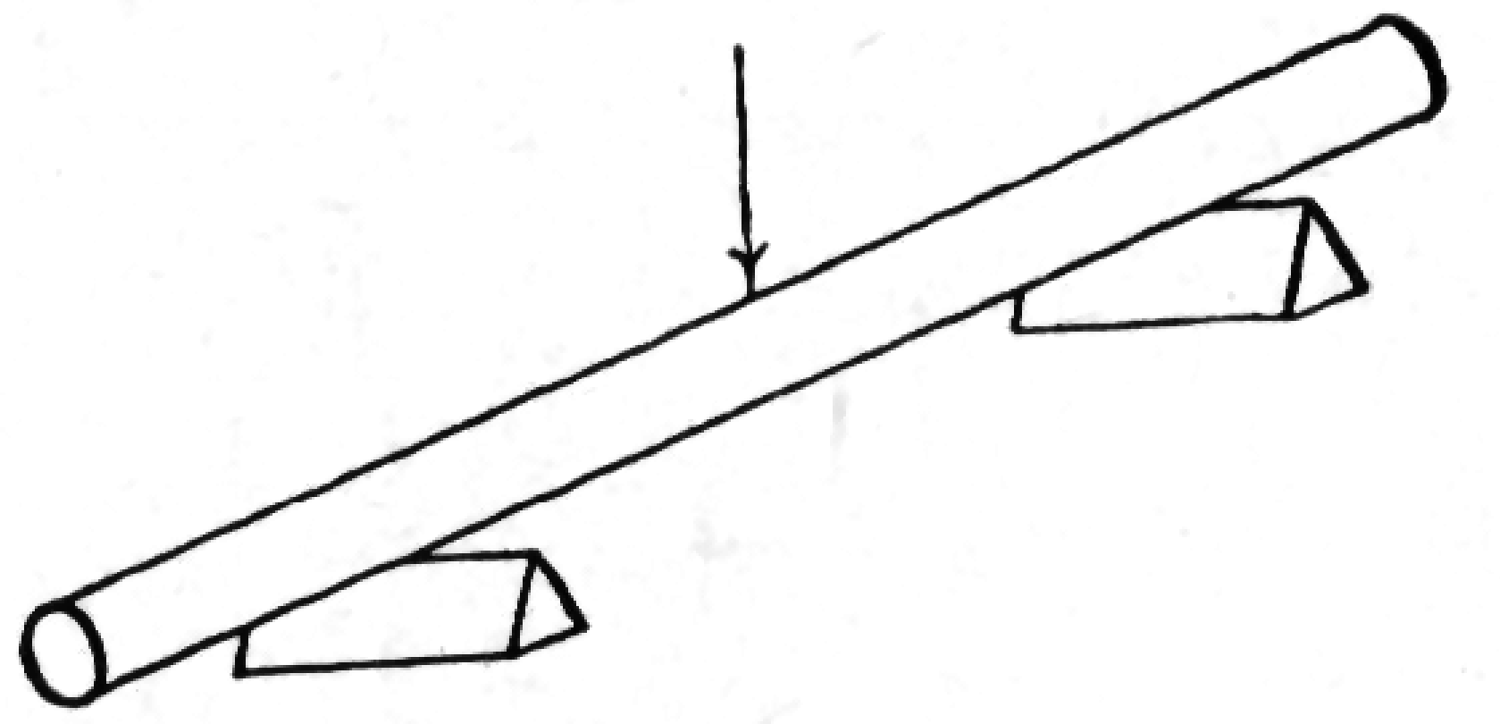


FIG. 3–14. A test specimen subjected to a transverse load.

The test bar is supported as a simple beam and loaded at its midpoint until failure occurs. The load at fracture and deflection of the midpoint at fracture are indicated on graduated dials. A very common test specimen is a 1.2-in. round bar, 21 in. long, tested over an 18-in. span. Other brittle materials are often evaluated by a similar transverse bending test. The result of a transverse test is generally expressed as the *modulus of rupture*—a mathematical relationship for expressing the transverse breaking strength of a material which is of a low order of ductility and in which stress and strain are not proportional.

3–9. Compressive Test. The compressive test is more frequently used to determine the strength of built-up or composite structures such as concrete and bearing metals than it is to indicate the compressive strength of homogeneous materials.

Principles involved in compression testing (see Fig. 3–2) are similar to those involved in tension testing, in that a yield point (for metals) is observed and Hooke's law of elastic proportionality of stress and strain applies. In the ductile materials, such as wrought steels, it is generally observed that the elastic limit and yield strength obtained by a compression test are the same as those obtained by a tension test. Compression tests on gray cast-iron, however, show a different picture; and the compressive strength may be from 2 to 5 times as high as the tensile strength. This difference is attributed to the graphite flakes, which act as stress raisers under tensile loads. Reproducible results are more difficult than in tension testing because of (1) the tendency of the specimen to buckle; (2) the increasing friction between contact surfaces as the specimen expands; and (3) the difficulty of obtaining specimens whose contact surfaces are truly parallel.

3–10. Creep Test. Creep tests are generally based on time-temperature observations over long periods of time on test pieces which carry a definite fixed load at a constant temperature. From a series of tests at a single temperature, a limiting creep stress may be estimated for a certain arbitrary small rate of creep. To reduce the time of testing, short-time tests have been tried, but their results do not always agree with those obtained from tests continued for long periods. One test method for steel consists of determining the stress that produces a maximum permissible strain of 1 per cent in 100,000 hr. Another consists of determining the stress that causes an initial elongation of less than 0.5 per cent of the prescribed gauge length during the first 24 hr of loading and a steady extension of less than 1 millionth of an in. per in. per hr for the next 48 hr. A safe stress is considered to be ⅔ of the time-yield value. The creep generally varies directly as the temperature and indirectly as the grain size. Coarse-grained steels resist plastic flow to a greater extent than do fine-grained steels.

Creep of metals becomes important in (1) soft metals used at room temperature, such as lead pipes, white metal bearings, etc.; (2) steam and chemical plant parts, which operate at temperatures of over 1000F; and (3) furnace parts.

3–11. Damping Test. Damping is the capability of a material to damp out vibratory or harmonic stresses by conversion of the energy into heat. An index of its value is frequently obtained from a bar set into torsional vibration, the decreasing amplitudes being recorded. There are large differences in the damping capacity between riveted and welded articles and between steels and gray cast-irons.

3–12. Hardness Test. Hardness is generally defined as the resistance to permanent deformation, and it is one of the important physical properties of a metal. The hardness plays a significant part in the machinability of a metal, but such factors as work-hardening capacity, abrasive nature, and tendency to adhesion of the chip to the tool must also be con-

TABLE 3–1

APPROXIMATE RELATIONS BETWEEN HARDNESS AND TENSILE STRENGTH OF SAE STEELS

Brinell		Vickers (Firth-Diamond)	Rockwell		Shore	Tensile Strength
Diam. in Mm. 3000 Kg., Load, 10 Mm. Ball	Hardness Number	Hardness Number	C Scale, 150 Kg., Load, 120 Deg. Diamond Cone	B Scale, 100 Kg., Load, 1/16 In. Diam. Ball	Scleroscope Number	1000 Lb. Per Sq. In.
2.20	780	1,150	70	...	106	384
2.25	745	1,050	68	...	100	368
2.30	712	960	66	...	95	352
2.35	682	885	64	...	91	337
2.40	653	820	62	...	87	324
2.45	627	765	60	...	84	311
2.50	601	717	58	...	81	298
2.55	578	675	57	...	78	287
2.60	555	633	55	...	75	276
2.65	534	598	53	...	72	266
2.70	514	567	52	...	70	256
2.75	495	540	50	...	67	247
2.80	477	515	49	...	65	238
2.85	461	494	47	...	63	229
2.90	444	472	46	...	61	220
2.95	429	454	45	...	59	212
3.00	415	437	44	...	57	204
3.05	401	420	42	...	55	196
3.10	388	404	41	...	54	189
3.15	375	389	40	*110*	52	182
3.20	363	375	38	*110*	51	176
3.25	352	363	37	*109*	49	170
3.30	341	350	36	*109*	48	165
3.35	331	339	35	*108*	46	160
3.40	321	327	34	*108*	45	155
3.45	311	316	33	*107*	44	150
3.50	302	305	32	*107*	43	146
3.55	293	296	31	*106*	42	142
3.60	285	287	30	*105*	40	138
3.65	277	279	29	*104*	39	134
3.70	269	270	28	*104*	38	131
3.75	262	263	26	*103*	37	128
3.80	255	256	25	*102*	37	125
3.85	248	248	24	*101*	36	122
3.90	241	241	23	100	35	119
3.95	235	235	22	99	34	116
4.00	229	229	21	98	33	113
4.05	223	223	20	97	32	110
4.10	217	217	..	96	31	107
4.15	212	212	..	96	31	104
4.20	207	207	..	95	30	101
4.25	202	202	..	94	30	99
4.30	197	197	..	93	29	97
4.35	192	192	..	92	28	95
4.40	187	187	..	91	28	93
4.45	183	183	..	90	27	91
4.50	179	179	..	89	27	89
4.55	174	174	..	88	26	87
4.60	170	170	..	87	26	85
4.65	166	166	..	86	25	83
4.70	163	163	..	85	25	82
4.75	159	159	..	84	24	80
4.80	156	156	..	83	24	78
4.85	153	153	..	82	23	76
4.90	149	149	..	81	23	75
4.95	146	146	..	80	22	74
5.00	143	143	..	79	22	72
5.05	140	140	..	78	21	71
5.10	137	137	..	77	21	70
5.15	134	134	..	76	21	68
5.20	131	131	..	74	20	66
5.25	128	128	..	73	20	65
5.30	126	126	..	72	..	64
5.35	124	124	..	71	..	63
5.40	121	121	..	70	..	62
5.45	118	118	..	69	..	61
5.50	116	116	..	68	..	60
5.55	114	114	..	67	..	59
5.60	112	112	..	66	..	58
5.65	109	109	..	65	..	56
5.70	107	107	..	64	..	55
5.75	105	105	..	62	..	54
5.80	103	103	..	61	..	53
5.85	101	101	..	60	..	52
5.90	99	99	..	59	..	51
5.95	97	97	..	57	..	50
6.00	95	95	..	56	..	49

Emphasis is laid upon the fact that this table gives the *approximate* relationship of Brinell, Rockwell and Scleroscope hardness values. It is impossible to give more than an approximate relationship due to the inevitable influence of size, mass, composition and method of heat treatment. Where more precise factors are required they should be especially developed for each steel composition, heat treatment and part. Figures for Rockwell B scale over 100 are included merely for convenience and probably are less accurate than the remainder of the data.

From Republic Alloy Steels (*1943 ed.*)

sidered. Hardness and tensile strength are closely related, as shown in Table 3–1. Wear resistance, like machinability, depends upon more than hardness alone, though it is probably the predominant factor. In general, the impact strength decreases as the hardness is increased, although there are important exceptions in the *blue brittleness* range and *temper brittleness* range of quenched and tempered steels, also, an austempered steel at 50 Rockwell C hardness is much tougher than one quenched and tempered to 50 Rockwell C. (See Table 10–6, Chapter 10.)

While many methods are used to determine hardness, there is no universally accepted test. Four of the most widely used will be considered here: the Brinell, Rockwell, Vickers, and Scleroscope methods.

Brinell Test. The Brinell tester (see Fig. 3–15) indicates the ability of the surface of the metal to resist penetration by a small ball that is propelled by a gradually applied force. The machine consists essentially of a small hydraulic press, operated by a small hand- or motor-driven pump and provided with a pressure gauge and a special contrivance for automatically holding the pressure. The piston of the press, which acts vertically downward, is provided on its end with a hardened steel ball, 10 mm in diameter (a 5-mm ball may be used; but it is not considered a standard test), by means of which an impression is made on the surface of the specimen resting on a firm but adjustable base. The operation of the machine is very simple. The specimen, the surface of which has been ground to remove scale, is laid on the base and is then brought in contact with the ball by adjustment of the base, or platform. By means of the pump, maximum pressure is attained and maintained for sufficient time so that the steel ball is pressed into the surface. Then the pressure is released, the base is lowered, and the diameter of the impression made in the specimen is measured by means of a micrometer microscope fitted with a millimeter scale. The applied load divided by the spherical area of the impression in square millimeters gives the Brinell hardness number. One formula for making this calculation is:

$$BHN = \frac{P}{\frac{\pi D}{2}\left(D - \sqrt{D^2 - d^2}\right)}$$

where P = load, D = 10 mm diameter of the ball, d = diameter of the impression, and BHN = the hardness number.

For the testing of steels and cast-irons, the load is 3,000 kg held for 10 sec minimum, while the load for softer metals (bronzes, aluminum, etc.) is 500 kg held for 30 sec minimum. The sample under test should be supported firmly so that applied stress acts in a plane normal to specimen.

A number of special precautions to be observed in applying the Brinell test are: it should not be used (1) on samples of very soft metals less than about 0.5 in. thick, (2) on samples so small as to allow plastic flow at the edges as a result of the ball impression, and (3) on very hard steels which may either break or distort the steel ball. The maximum Brinell hardness for which a steel ball is usable is 500. Tungsten carbide balls are used on metals testing up to 800 Brinell. Oxide films on steel and iron should be removed, and the surface should be reasonably smooth and free from defects and indentations or ridges.

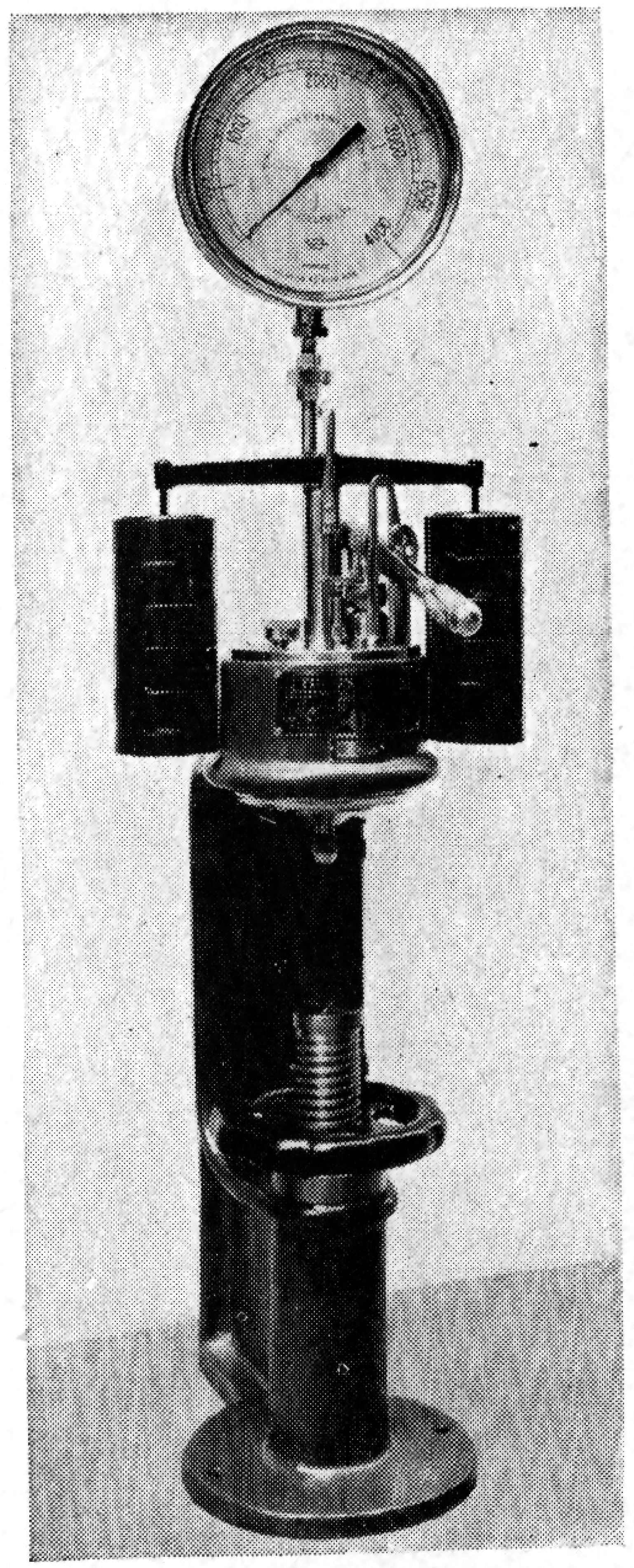


FIG. 3–15. Standard Brinell hardness tester. (Courtesy of American Machine and Metals Inc., East Moline, Ill.)

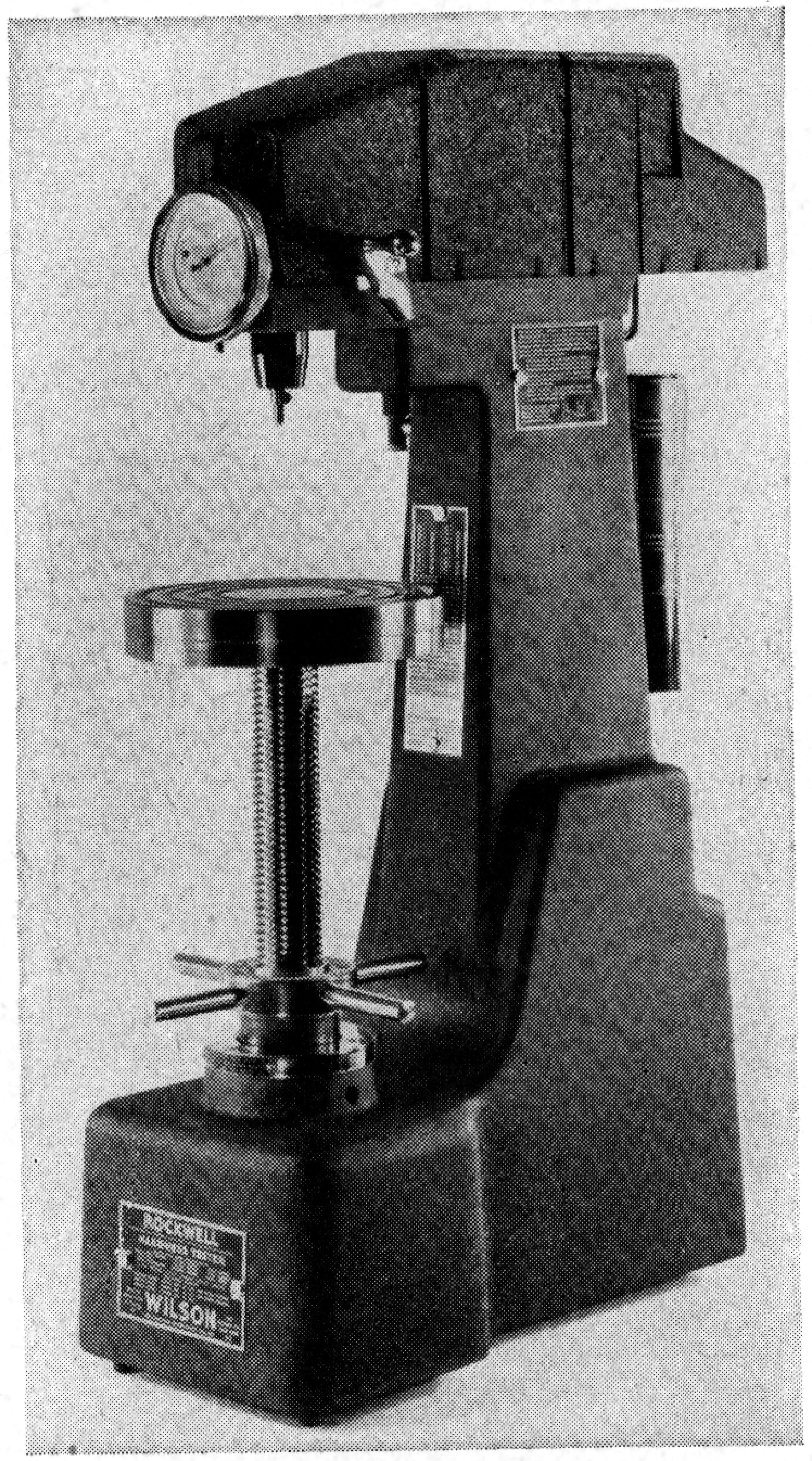


FIG. 3–16. Production type of Rockwell hardness tester. (Courtesy of Wilson Mechanical Instrument Co. Inc., New York, N. Y.)

Because of the relatively large area of deformation, the Brinell tester is applicable for the testing of gray cast-iron and similar metals of non-uniform structure. Where such identation might be objectionable on finished surfaces, other methods of testing must be used.

Rockwell Hardness Test. The Rockwell hardness tester (see Fig. 3–16)

is similar to the Brinell, in that it employs an anvil or base and that the effect of the penetration is circular. The difference between the machines, however, is greater than the similarity. The force on the Rockwell machine is applied mechanically through a system of weights and levers, and the penetrator consists of a 120-degree diamond-pointed cone or a $\frac{1}{16}$-in. diameter steel ball. Furthermore, the basis of the Brinell test is the area of a spherical indentation, while the Rockwell number is based upon the increment of penetration caused by an increment of load. This increment of depth due to the increment of the load is 0.00008 in. for each additional hardness point on the scale. Thus, a difference of 4 in the Rockwell hardness means that the penetration depth is 4 × 0.00008 in., or 0.00032 in., deeper in the softer of the two specimens. In addition, this depth is indicated to 0.001 in., and the Rockwell hardness number is read directly from the dial. The dial is equipped with two scales known

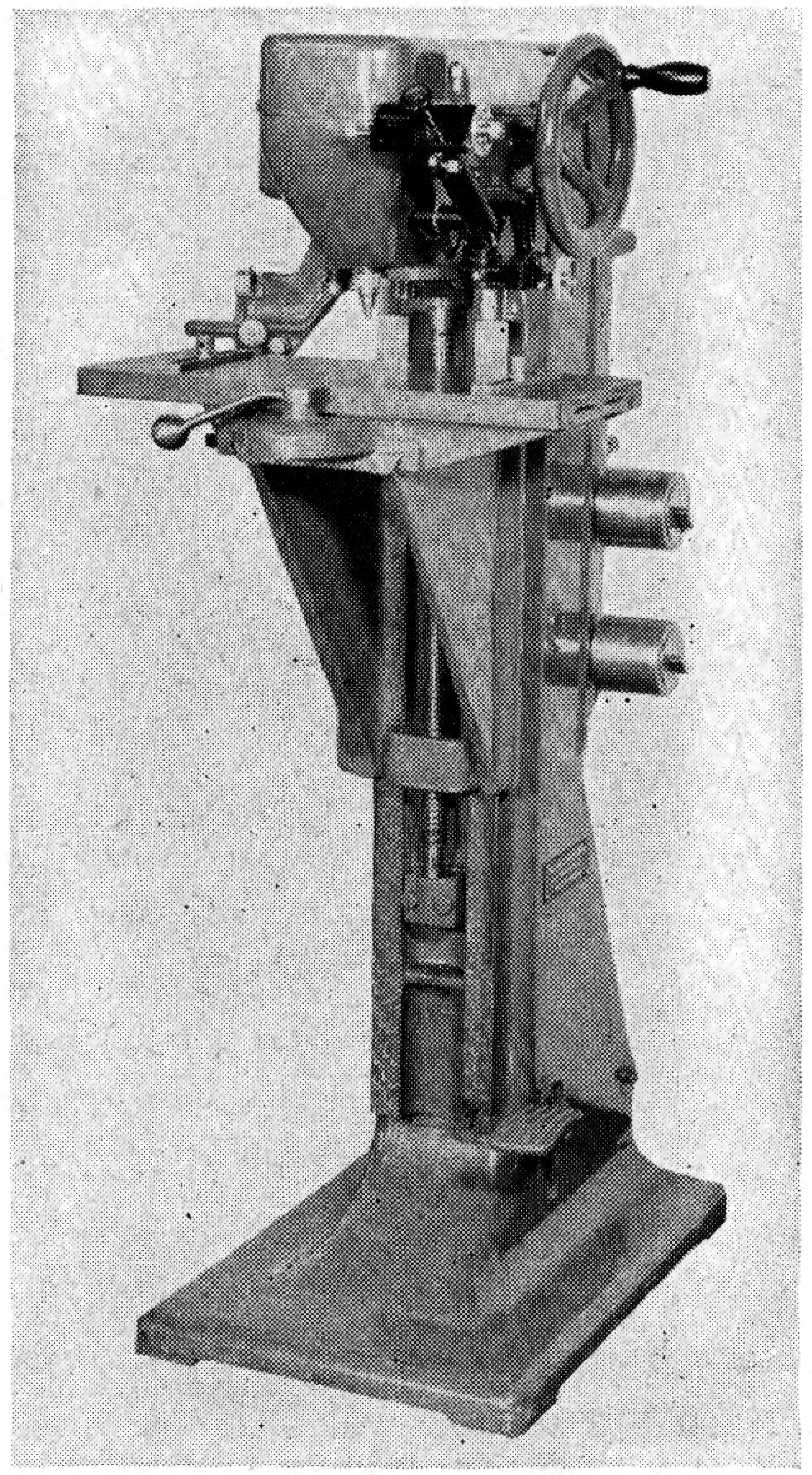


FIG. 3–17. Vickers hardness tester. (Courtesy of American Machine and Metals Inc., East Moline, Ill.)

as the B and C scales, which are used for soft and hard steels, respectively. For soft metals, the $\frac{1}{16}$-in. hardened steel ball is used as a penetrator with a major load of 100 kg and the hardness readings are made on the B scale. When steels of greater hardness are tested, the diamond-point cone penetrator is used with a major load of 150 kg; and the reading, in this instance, would be made on the C scale. The dial is graduated from 0 to 100.

In a test with the Rockwell hardness tester, the work is raised by means of the handwheel against the penetrator until a small pointer indicates the application of a minor load of 10 kg, which is initially applied to take up any slack in the machine and to overcome surface irregularities of the material. The dial is then set to zero of the C scale, and the major load is applied by a slight pushing back of a handle. When the large pointer of the dial comes to rest, the handle is pulled forward to its original position; and the reading is made on the appropriate scale.

Surface hardness of nitrided and carburized steel and very thin sheets of steel, brasses, and bronzes is tested with the Rockwell Superficial Tester, using minor loads of 3 kg and major loads of 15, 30, or 45 kg.

Vickers Hardness Test. Basically similar in principle to the Brinell and the Rockwell, the Vickers machine (see Fig. 3–17) employs a diamond pyramid indenter whose apex is accurately ground to an included angle of 136 degrees. The indentation is square at the plane of the surface. Measurements are made by reading the diagonal of the square with an ocular microscope that reads accurately to 0.001 mm, is pivoted on the machine, and is focused automatically. The machine is adapted for use on very hard surfaces and thin casehardened products; and, since the impression is small, it may be used for final checking of finished surfaces. The applied load may be varied since the Vickers hardness is the force divided by the area of the impression and may be written as:

$$VH = \frac{2P \sin \theta/2}{D^2}$$

where P = load in kilograms
D = average length of two diagonals in millimeters
θ = apex angle = 136 degrees
VH = Vickers hardness

The duration of the load varies from 10 to 30 sec.

Scleroscope Hardness Test. The Shore Scleroscope (see Fig. 3–18) consists of a small diamond-faced tup, enclosed in a tube and actuated by a knurled knob. To make a determination, the instrument is placed in the vertical position with the lower end resting firmly upon the smooth and polished surface of the metal to be tested. Then the tup is released and dropped from a definite and fixed height. The height of the rebound, which may be read on a dial at the upper end of the instrument, is taken as a measurement of the hardness. Notwithstanding the fact that the results obtained by this instrument are sometimes erratic, especially if the surfaces of the different spots tested have not been properly and uniformly polished, it is a valuable instrument for comparing the surface hardness of the different parts of a body that is too large to be tested in any other way, as it can be dismounted from its support and placed on a swing arm or even held by the hand. It also possesses the advantage that the tests may be made upon the finished article without injury to its surface, since the impression made is quite small.

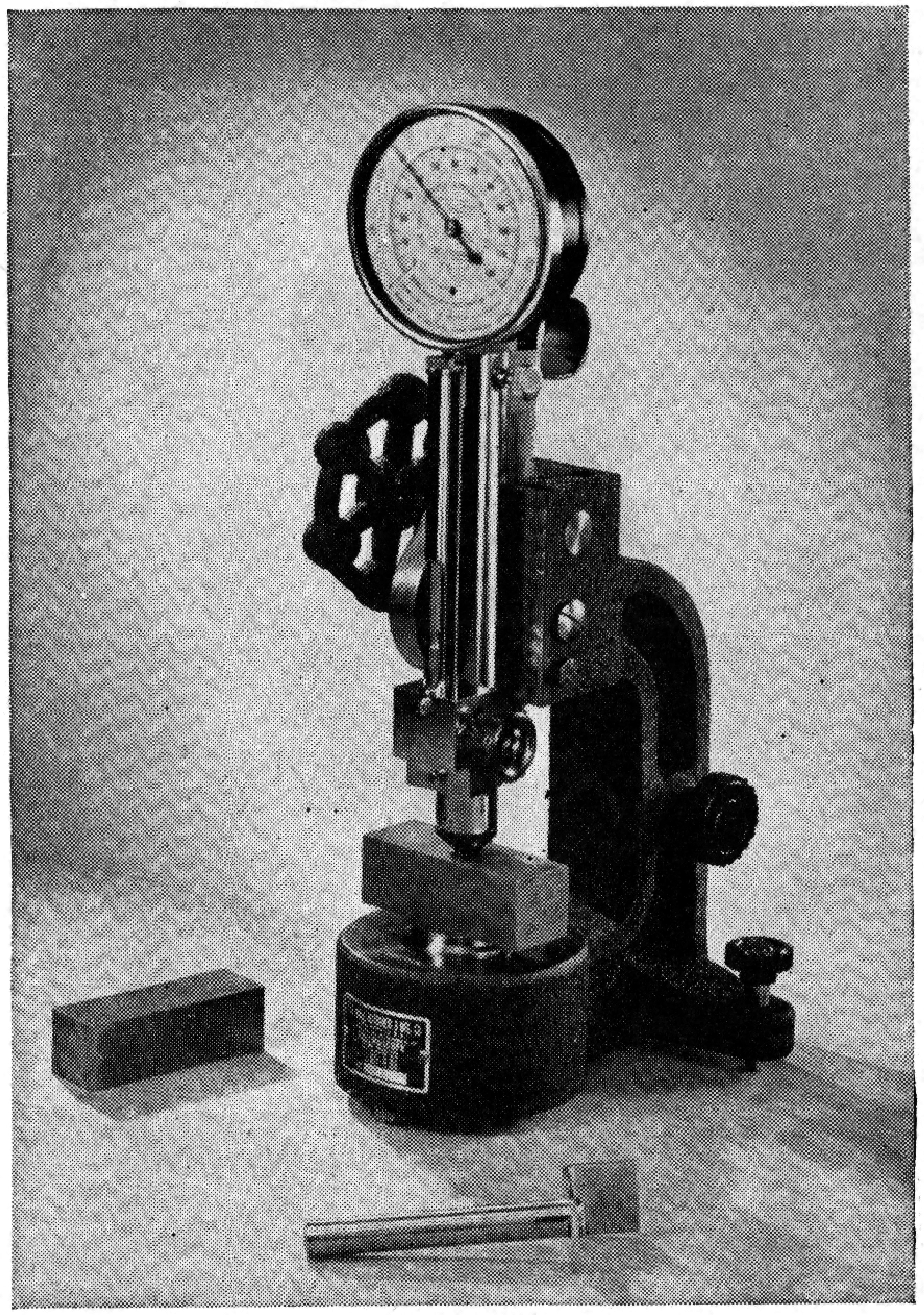


FIG. 3–18. Shore Scleroscope hardness tester. (Courtesy of Shore Instrument and Manufacturing Co., Jamaica, N. Y.)

QUESTIONS AND PROBLEMS

1. Define the following: ductility, malleability, shear, damping, ultimate strength, proportional limit, elastic limit, yield point, stress, strain, elongation.
2. What specific properties of metals are explored by means of (1) physical and (2) mechanical tests?
3. Which is the better means of determining the selection of a part for service—chemical analysis or mechanical tests? Why?

4. The following data were obtained from the tensile testing of a standard round test specimen (0.505 in. diam, 2 in. gauge length): yield point, 15,470 lb; ultimate strength, 26,650 lb; final diam 0.348 in.; final length, 2.630 in. Compute the yield point and ultimate strength in psi and the reduction of area and elongation in per cent.
5. Draw stress-strain curves for low-carbon steel and gray cast-iron test bars. Indicate the point on the curve at which failure occurs.
6. Name an appropriate test or tests for each of the following: a drive shaft, a tie rod, a cutting tool, a wrist pin, a cylindrical cast-iron column.
7. Is the transverse test applicable to ductile metals? Give reasons.
8. Which is the more desirable for a machine part subject to frequent shocks—high or low damping capacity?
9. Assume the diameter of an impression made by a Brinell tester to be 3.75 mm. Compute the BHN (diam of ball = 10 mm applied load 3,000 kg).
10. In what basic respects do the Vickers and Rockwell testers differ from the Brinell and Scleroscope?
11. Select a method whereby the hardness of each of the following metals may be determined: gray cast-iron, very hard tool, soft copper sheet ⅛ in. thick, a pump shaft with a surface hardness 0.004 in. thick.
12. Define "stress raisers."
13. What type of metals have no yield point?

REFERENCES

For a more complete treatment, including standards, dimensions, and specifications of the tests herein discussed, the reader is referred to the following American Society for Testing Materials Designations in Part 1 of ASTM Standards, 1944:

E8 –42	Tension Testing of Metallic Materials
E9 –33T	Compression Testing of Metallic Materials
E23 –41T	Impact Testing of Metallic Materials
A260–42T	Torsion Tests of Cast-Iron
A256–42T	Compression Testing of Cast-Iron
A48 –41	Standard Specifications for Gray Iron Castings (transverse test)
E21 –43	Short-Time Elevated-Temperature Tension Tests of Metallic Materials
E10 –27	Brinell Hardness of Metallic Materials
E18 –42	Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials
E48 –43T	Tentative Hardness Conversion Tables for Steel (Relationship between Diamond Pyramid Hardness, Rockwell Hardness, and Brinell Hardness)

Other sources of information include:

ASTM Testing Procedures.

Leigh and Mangold, *Practical Mechanics and Strength of Materials.* McGraw-Hill Book Company, New York.

Moore, H. F. and Kommers, J. B., *Fatigue of Metals.* McGraw-Hill Book Company, New York.

Seeley, F. S. *Resistance of Materials.* John Wiley & Sons, Inc., New York.

CHAPTER 4

THE MANUFACTURE OF IRON

4–1. Introduction. The production of iron and steel surpasses in importance all other events in the whole history of the unfolding of civilization. To their development, more than to that of any other metals, may be attributed the phenomenal industrial progress which has been made in the past two centuries. Were they to be withdrawn, only the barest and most primitive existence imaginable would be possible. For our present economy, machines and tools, implements and weapons, locomotives, automobiles and airplanes, bridges and ships—all made largely of iron and steel—are indispensable.

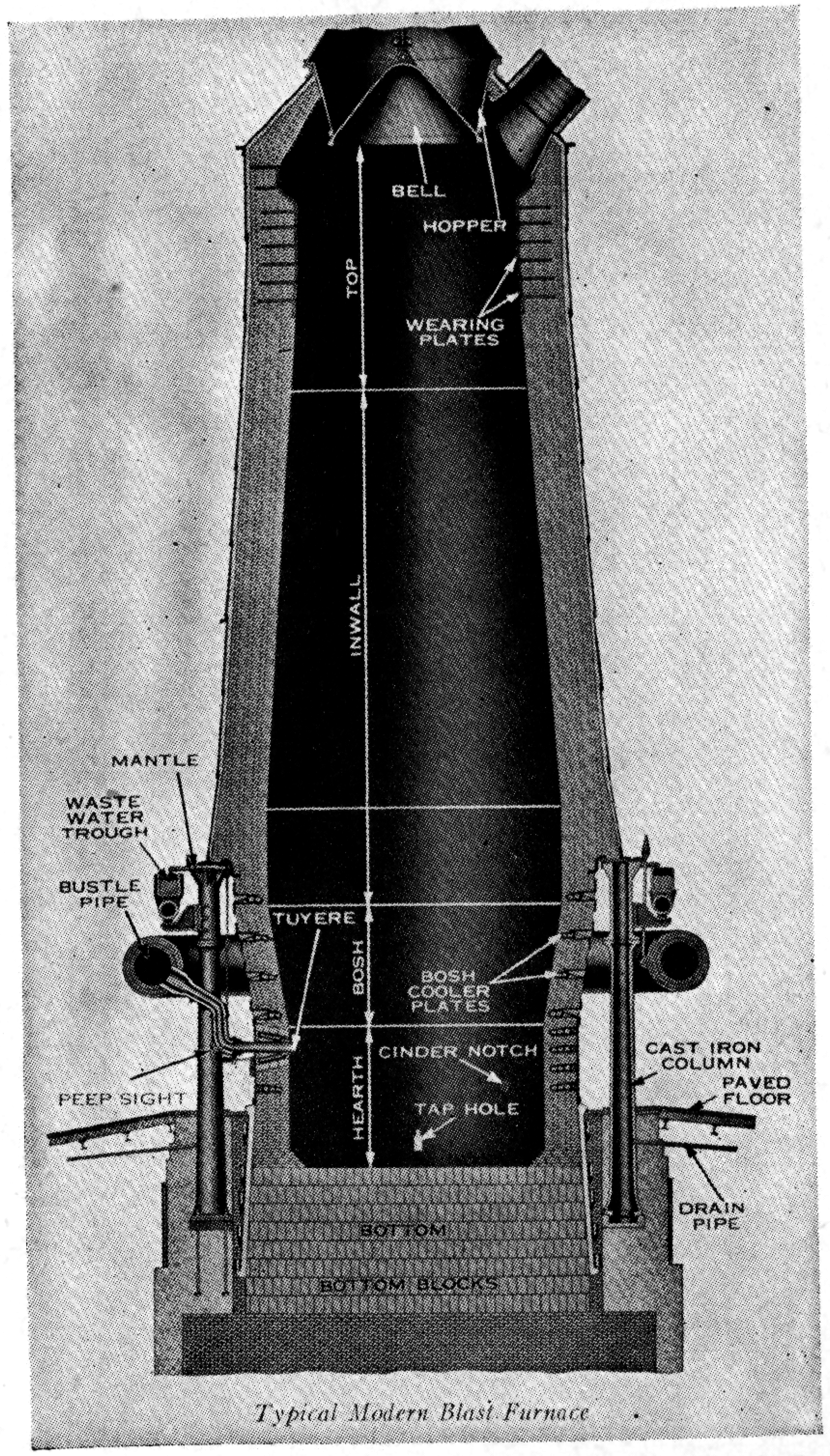
This valuable metal was first produced by our primitive ancestors when they surrounded their campfires with iron-bearing ore which, upon exposure to the heat of the charcoal fire, was reduced to metallic iron. As this reduction took place below the melting point of the metal, it entailed long exposures. And, unlike the product of modern direct reduction or smelting methods, primitive iron was malleable or workable in a manner comparable to dead soft steel.

The progress of civilization would truly be very slow were we to depend upon such methods for the production of this essential metal. Facilitated by the development of forced draft methods and a growing appreciation of the potentialities of iron and steel, consistent efforts were made early in the fourteenth century to produce the metal in larger quantities and in less time than had been possible before. The first furnace for smelting iron in America was built at Lynn, Massachusetts, in 1645 and had a capacity of 8 tons of iron per week! Coincidentally with our railroad expansion era following the Civil War, the evolution of iron smelting progressed rapidly, resulting in the higher efficiencies and incomparably higher capacities of the blast furnaces of today.

Anyone who is interested will find most enchanting the history of these earlier, as well as later, efforts to produce iron, since the development of iron closely parallels the progress of civilization.

4–2. Blast Furnace. The first metallurgical operation in the manufacture of iron and steel is the conversion of an iron-bearing oxide into metallic iron. This is accomplished in a blast furnace, shown in Fig. 4–1.

As intimated, the impetus of the continually increasing demand for iron and steel resulted in the evolution of the early small and relatively inefficient charcoal-burning furnaces into the modern blast furnaces having capacities of more than 1,200 tons of iron per day and operating at temperatures of over 3000F. Unlike their predecessors, the blast furnaces of today use for fuel a specially prepared coke, which possesses a sufficiently high crushing strength to sustain the total weight of the load in the furnace.



Typical Modern Blast Furnace

Courtesy of Harbison-Walker Refractories Co., Pittsburgh, Pa.

FIG. 4-1. Modern Blast Furnace.

The furnace itself is a large steel-encased structure, lined with a high-grade firebrick from 1½ to 5 ft thick. It is cylindrical in section and its diameter increases from its smallest diameter at the top almost down its entire length. Its height varies from 75 to 100 ft or more, with a diameter at the widest part of from 20 to 30 ft. The whole structure rests on a concrete and brick foundation, 10 to 15 ft thick.

The top of the furnace is closed with an ingenious device consisting of two cone-shaped, cast-iron *bells* and two *hoppers*. The materials which form the charge are hoisted in a steel car called *skip* on a skipway to the top of the furnace and are dumped into the small upper hopper. The base of this hopper is the small bell which rotates and discharges the materials into a larger hopper underneath. The upper bell then returns to its original position, after which the larger and lower bell opens and discharges the materials into the furnace. The gases generated in the furnace are thus prevented from escaping into the air and are led away from the furnace through large pipes or downcomers.

The hearth of the furnace serves as a receptacle for the molten iron and slag which constantly trickle down through the coke bed. Close to the bottom of the hearth is a tapping hole, through which the molten iron is drained. This opening is about 6 in. by 8 in. on the inside and tapers to about 8 in. by 10 in. on the outside. About 3 to 5 ft above the tapping hole and at some convenient angle, usually 90 degrees, is placed a *cinder notch* through which is drained periodically the slag or residue, consisting of the oxidized portions of the ore and the fluxing materials in the charge. The dimensions of the cinder notch are usually approximately twice those of the tapping hole. The furnace is tapped for metal every 6 hr, when about 300 tons are taken out. The slag is drained at least twice between each metal cast.

After being thoroughly dried or *burned in*, an operation usually carried out with hot gases and requiring a period of 10 days to 2 weeks, the furnace is continued in service without interruption for from 4 to 7 years.

The increasingly higher operating efficiencies and the improved quality of the refractory materials available for lining the furnace make possible the production of nearly 2,000,000 tons of metal with a single lining. It is even reported that a single furnace has produced 3,000,000 tons without relining.

Essential to the successful operation of the blast furnace is auxiliary equipment, such as heating stoves, dust catchers and washers, and powerful blowing engines which furnish from 50,000 to 100,000 cu ft of air per minute.

4-3. Heating Stoves. The stoves, of which there are no fewer than 4 for each furnace, are usually as large and as high as the blast furnace itself and are constructed with a heavy steel shell. They are used to preheat the air for the more efficient operation of the furnace. The hot gases carried away from the top of the furnace, after most of the flue dust has been removed, are washed and then burned within these stoves. Each stove consists of a combustion chamber and regenerative chamber, the latter consisting of a checkered brickwork extending the entire height of the stove. The gases burned in the combustion chamber pass from 2 to 4 times through the vertical regenerative flues which are thus heated. After the regenerative brickwork has been sufficiently heated, the gases are turned to another stove; and cold air from the compressors is introduced, which passes through the heated chamber until its temperature is raised from 1000F to 1400F. From here it is led through a large hot blast pipe into the *bustle* which encircles the furnace, and through 12 or 16 tuyeres, or water-cooled openings, into the furnace at a pressure of 15 to 20 psi. Control over the furnace temperature is necessary for the production of different types of iron and to offset heat absorption by the vapor content of the air, as well as by other conditions. This control is conveniently provided by by-passing cold air into the hot-blast main. Usually only 1 stove preheats the air while the other 3 are being heated. They are alternated about every 2 hours.

4–4. Furnace Charge. Fundamentally, the principle on which the blast furnace operates has remained much the same since its inception. Improved operational techniques, however, have resulted in incomparably higher efficiencies and production.

The materials which constitute a charge or *burden* for a blast furnace are coke, ore, and either limestone ($CaCO_3$) or dolomite which is a calcium magnesium carbonate (Ca Mg)CO_3. The selection of $CaCO_3$ or (Ca Mg)CO_3 depends largely on the subsequent use which will be made of the residue or slag removed from the furnace. These materials are placed in the furnace so as to form alternate layers of coke, ore, and limestone, respectively. For each ton of metallic iron produced, there will also be produced about ¾ ton of slag. To produce these amounts, nearly 2,000 lb of coke will be consumed, 4,000 lb of ore, and 1,000 lb of limestone, besides approximately 9,000 lb of air. These materials are charged continually to offset any shrinkage in volume and to keep the furnace full at all times. From 18 to 24 hours after they enter the furnace at the top, these materials emerge as metal and slag.

4–5. Coke. Coke is beneficiated by crushing and is charged in a size varying from 1 to 4 in. All fines (less than ¼ in.) are screened out. The function of the coke is to supply the gases and carbon to reduce the oxides, and to furnish heat for melting the metal and slag. Of the materials composing the charge, coke is the least affected by its passage through the furnace. On the hearth, it is burned into an ash, which combines with the flux and the impurities or gangue to constitute the slag.

4–6. Impurities. The only economical beneficiation of limestone is to crush it to about the same size as the lumps of coke—1 to 4 in. The limestone selected has a high purity and is free of extraneous materials.

The impurities normally associated with the iron oxide are characterized by high fusion temperatures, which make their separation from the ore either by oxidation or reduction relatively difficult. As shown by Table 4–1, the predominating constituents are silica and alumina. At elevated temperatures, the silica is highly acidic in its chemical reactions, while the alumina may be either weakly acidic or basic. When strongly basic substances, such as $CaCO_3$ and (Ca Mg)CO_3, are added to the furnace charge and heated to a temperature of between 1400 and 1600F, they decompose to form CaO, MgO and CO_2. While the CO_2 unites with other furnace gases, the CaO and MgO react with the silica to produce a fusible slag of a comparatively low melting point.

At higher temperatures in the lower parts of the furnace, particles of porous metallic iron, called sponge iron, absorb carbon, manganese, silicon, sulphur, and phosphorus from the carbon rich gases, and from the surrounding materials. When this sponge iron eventually reaches the fusion zone, it begins to melt; and, along with the slag globules, it continues to absorb heat and descends countercurrent and settles on the hearth or crucible. Because of its lower density, the slag remains on top of the iron.

TABLE 4–1

Typical Analyses of Iron Ores

	Fe	P	SiO_2	Mn	Al_2O_3	CaO	MgO	S	H_2O
Marquette...	56.82	0.135	15.47	0.08	1.25	0.67	0.327	0.007	0.944
Missabe.....	52.54	0.039	11.50	0.52	1.56	0.19	0.29	0.009	7.87
Missabe.....	47.47	0.067	6.09	1.43	0.83	0.25	0.32	0.008	16.80

Substances, which combine with other materials to render them more fusible or to absorb certain impurities, are generally referred to as *fluxes*. Thus, $CaCO_3$ and (Ca Mg)CO_3 are blast furnace fluxes.

4–7. Air. Besides sustaining combustion of the coke, air is also one of the most important of the raw materials entering the furnace. As pointed out previously, more of it is consumed per ton of metal than any other constituent. In view of its variable composition, especially as regards moisture content, efforts are constantly made to hold humidity to absolute minimums, since all water vapor reactions are endothermic and high water content results in high heat loss.

4–8. Ores. Iron is found more or less plentifully in almost all lands; yet, its existence in the pure metallic state is unknown. So strongly does it associate with other minerals that it is invariably found combined with those shown in Table 4–1. These worthless impurities are collectively called *gangue*. In order to make its smelting profitable and worth while, the ore must be sufficiently high in metallic iron and its gangue must be easily reducible.

The principal ores now commercially available for use are the red oxides called Hematites (Fe_2O_3) and the Magnetites (Fe_3O_4). The red hematite is an anhydrous oxide, identical in composition to red iron rust; and, when pure, it yields approximately 70 per cent metallic iron. The hematites constitute over 90 per cent of all ores mined and smelted in the United States. Although the magnetites yield 72.4 per cent metallic iron when pure, only approximately 5 per cent of the total output of iron and steel comes from this ore.

Other minerals of insignificant importance are Siderite ($FeCO_3$), Pyrite (FeS_2), and Limonite ($2Fe_2O_3 \cdot 3H_2O$). The latter is a hydrous oxide distinguishable from the red hematite only by the presence of its water of crystallization. These ores yield, when pure, approximately 48 per cent, 47 per cent, and 60 per cent metallic iron, respectively. The ores smelted in the United States at the present time range in iron content from 35 per cent to 65 per cent. Much lower grade ores are used in other parts of the world.

4–9. Chemistry of Process. The fundamental function of the blast furnace is to convert iron oxide into metallic iron. In one sense it is a concentrator, since it also separates the iron from its impurities and thus concentrates the desirable element. The reduction of the oxides is performed by the coke and the large volumes of reducing gases, produced by the combustion of coke, which ascend through the charge until they contact the ore in the upper part of the furnace.

The air blast which enters the furnace contains 23.2 per cent oxygen and 76.8 per cent nitrogen by weight. Immediately inside the furnace, this oxygen reacts with the highly heated coke, which consists of about 87 per cent carbon, and forms carbon dioxide: $C + O_2 \rightarrow CO_2$. At the high temperatures prevailing on the hearth, the CO_2 is rapidly reduced by the surrounding carbon: $CO_2 + C \rightarrow 2CO$. This highly reducing gas ascends through the materials and reacts with the gradually descending oxide at temperatures which range from approximately 1300 to 400F at the top of the stack. This reduction is effected in three stages, depending on the temperature in the various zones; thus: $3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$; $Fe_3O_4 + CO \rightarrow 3FeO + CO_2$; $FeO + CO \rightarrow Fe + CO_2$. The reduction of the oxide may also take place by its contact with the solid carbon of the coke at relatively low temperatures: $3Fe_2O_3 + C \rightarrow 2Fe_3O_4 + CO$; $Fe_3O_4 + C \rightarrow 3FeO + CO$; $FeO + C \rightarrow Fe + CO$. It is also possible under proper conditions to obtain a reduction of the oxide by carbon in a direct way; thus: $Fe_2O_3 + 3C \rightarrow 2Fe + CO$.

At the high temperatures which prevail in the lower parts of the furnace, several other reactions proceed gradually and simultaneously to reduce the oxides of manganese, silicon, and phosphorus.

The manganese entering the furnace as an ingredient of the ore, usually as manganese dioxide or the oxide Mn_3O_4, is reduced in a manner similar to that for iron oxide, by solid carbon according to equations: $Mn_3O_4 + C \rightarrow 3MnO + CO$; $MnO + C \rightarrow Mn + CO$. By controlling the basicity of the slag and operating the furnace at higher temperatures, a high percentage of the manganese will be reduced and dissolved in the iron. Under normal operating conditions, however, only from 50 per cent to 75 per cent of the oxide will be reduced to metallic manganese. The remainder is taken up by the slag.

Silicon is introduced in the charge as SiO_2 and is also reduced by solid carbon to Si: $SiO_2 + 2C \rightarrow Si + 2CO$. The amount of silicon dissolved in the iron depends largely on the furnace temperature and the chemistry of the slags. High temperatures and acid slags favor maximum reduction. Under normal operating furnace conditions, only about 10 per cent of the SiO_2 is reduced, all of which enters into solution with the iron as iron silicide, FeSi. The remainder of the silica combines with the CaO and other bases in the fusion zone to form complex silicates, which compose the slag.

The phosphorus enters the furnace as a part of the ore and is in the form of phosphates P_2O_5. It is completely reducible at high operating temperatures by solid carbon to phosphorus according to equation: $P_2O_5 + 5C \rightarrow 2P + 5CO$. Since all of this phosphorus dissolves in the iron, control of the phosphorus content of pig irons must be obtained through the selection of proper raw materials and proper furnace temperature. And, since the elimination of phosphorus under acidic conditions is not possible, pig irons suitable for conversion into steels by the acid Bessemer and acid open-hearth processes must contain less phosphorus than is allowable in these steels.

About 90 per cent of the sulphur is introduced into the furnace with the coke in the form of FeS. The remainder comes from the ore and the limestone. In the presence of a large volume of a highly basic slag and high temperatures, sulphur is, along with manganese and silicon, largely controlled by operating conditions and by selection of raw materials. Because FeS is an iron compound, it dissolves readily in the iron unless it is transformed into a compound by combining with some element other than iron. This is accomplished by means of the CaO and C thus: $FeS + CaO + C \rightarrow Fe + CaS + CO$. The CaS becomes a part of the slag. The amount of sulphur remaining in the metal is governed by the basicity of the slag $\frac{\text{Per cent Bases}}{\text{Per cent Acids}}$, the temperature at the upper portion of the hearth, the ratio of slag to metal, and the amount of sulphur in the coke. Sulphur is an undesirable element in steels and cast-irons, because it tends to make the latter hard and brittle, while high sulphur steels are hot *short*, or weak when hot.

Aside from the oxides of magnesium, aluminum, calcium, and silicon, the principal slag-forming compounds, other constituents of the gangue are not reduced in the blast furnace but pass into the slag as oxides. According to a fundamental metallurgical law, reduced materials enter the metal while the oxidized substances constitute the slag.

4–10. Products of the Blast Furnace. As pointed out above, the reduction of the iron oxide and the combining of the gangue with the flux and coke ash yield two products, metallic iron and slag. The iron is the raw material, which is subsequently remelted or refined for the production of all commercial iron and steel products. The slag is a by-product which is pulverized and used either for railroad ballast or for grading lowlands, or it may be used as a constituent of portland cement.

TABLE 4–2

CHIEF METALLIC PRODUCTS OF BLAST FURNACE

Product	Maximum Range in Per Cent of				
	Silicon	Sulphur	Phosphorus	Manganese	Total Carbon
Foundry pig irons	1.00–4.00	0.04–0.10	0.10–2.00	0.20–1.50	3.00–4.50
Graded in steps of	0.50	0.01	0.20	0.20	—
Northern foundry	1.75–2.50	Under 0.05	0.150–0.70	0.5 –1.00	4.0 –4.3
Southern foundry	1.75–2.25	Under 0.05	0.7 –0.9	0.40–0.75	3.75–4.1
Malleable pig, standard	1.25–2.25	Under 0.05	0.1 –0.19	0.4 –1.00	3.75–4.30
Graded in steps of	0.25	—	0.05	0.20	—
Gray forge	1.20–1.75	Under 0.05	0.1 –0.35	0.5 –1.00	4.15–4.40
Puddling iron	0.75–2.50	Under 0.15	0.1 –0.50	0.5 –1.00	4.10–4.40
Acid pig, Bessemer	1.00–2.25	Under 0.045	0.04–0.1	0.5 –1.00	4.15–4.40
Open-hearth	1.0 –1.50	Under 0.045	Under 0.05	0.5 –1.50	4.15–4.40
Basic pig, open-hearth	Under 1.50	Under 0.05	0.11–0.90	0.4 –2.0	4.10–4.40
Bessemer or Thomas	0.5 –1.00	Under 0.20	1.9 –2.5	1.5 –2.5	3.50–4.0
Duplex iron	1.2 –1.75	Under 0.060	0.7 –1.5	0.4 –0.90	4.00–4.20
Special low phosphorus	Under 2.00	Under 0.035	Under 0.035	Under 2.00	—
Spiegel (three grades)	Under 1.25	0.03–0.05	0.14–0.25	16–30	5.0 –6.5
Silicospiegel	8.0–15.00	Under 0.02	Under 0.15	15–20	—
Ferromanganese	0.5 –1.00	Under 0.05	0.2 –0.35	78–82	6.5 –7.5
B.F. ferrosilicon, Silvery pig	6.00–17.00	Under 0.05	0.10–0.40	0.30–2.00	0.75–1.0
Ferrophosphorus	1.5 –1.75	Under 0.05	15–24	0.07–0.50	1.10–2.0

As a result of a practice, long discontinued, of casting the molten metal from the furnace into sand molds having the shape of a pig trough, the product of the blast furnace is known as *pig* iron. See Table 4–2.

Disposal of the metal today takes two forms—machine casting and hot metal car. In machine casting, the molten metal flows into ladles and then through troughs or runners into slowly moving metallic molds attached to an endless chain. Each mold has overlapping edges so that casting may be continuous without undue spillage. The molds and the metal are cooled in transit by various devices, and the pig iron is dumped for shipment or storage.

When the blast furnace is coordinated with steel-producing furnaces, as is most frequently the case, the molten metal is transferred in a hot metal car or mixer and charged directly into these furnaces for refinement. These cars are constructed with a well insulated steel outer shell so that metal may be retained in a molten state for several hours if necessary. Their capacity varies from 75 tons to nearly 200 tons.

Pig iron is neither malleable nor ductile and is the crudest form of iron. It is unsuitable for use other than for conversion into cast-iron or steel. Its hardness and structure are determined by its analysis; and its classification, or grade, is based principally on the percentage of silicon, phosphorus, sulphur, and manganese, respectively. Pig irons are also classified according to their suitability for subsequent conversion into castings, wrought iron, or steel as (a) foundry pig for making gray iron castings, (b) malleable pig for making malleable castings, (c) basic pig for basic open-hearth steel processes, (d) gray forge, for making wrought iron, and (f) low phosphorus pig for conversion into steel by the acid open-hearth and acid Bessemer processes.

QUESTIONS AND PROBLEMS

1. Describe fully the functions of a blast furnace and give the approximate temperature levels with the corresponding reactions.
2. Explain in detail the chemical functions of $CaCO_3$ or $(Ca\,Mg)CO_3$ in the blast furnace.
3. Name the impurities known as "gangue" associated with iron.
4. Make a list of usable metals found (1) in the pure slate and (2) as oxides.
5. List the impurities which are *oxidized* and those which are *reduced* in the blast furnace.
6. Trace, by means of equations, the reduction of Fe_2O_3 and Fe_3O_4 in the blast furnace.
7. What conditions determine the solubility of Mn, Si, S, and P in pig iron?
8. What elements in pig iron most influence its cost and subsequent use?
9. Give the analyses of pig iron for conversion into gray cast-iron and malleable cast-iron.
10. Give the analyses of pig iron suitable for conversion into steel by acid Bessemer and basic open-hearth processes.

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CHAPTER 5

CASTING PROCESSES

5–1. Introduction. Despite those factors which have favorably affected both the quantity and quality production of many complex shapes by welding or hot plastic working, a substantial tonnage of important engineering materials is produced yearly by casting, a process carried out in iron and steel foundries and in die-casting shops.

Reasons for the use of castings are based on sound economics and engineering practice. For example, some simple parts in small quantities may be satisfactorily produced at a lower cost by casting than by drop-forging or by welding of rolled steel shapes, and so casting is frequently used. Besides this, some sections are so complex as to render their manufacture by means other than casting difficult or practically impossible. As pointed out later, only a relatively small proportion of the world's total production of metallic products is used in the form of castings. But, since this amount remains substantially the same each year, it indicates that there is an essential need for cast metal products and that, proportionately, they are as indispensable for engineering needs as the wrought products.

5–2. Definition of Casting. A casting may be defined as the product obtained by the solidification of molten metal in a metal or refractory mold, designed to conform to the shape of the desired part.

5–3. Casting Processes. In the order of their commercial importance, the principal methods employed for the production of castings are (1) sand-casting, (2) die-casting, (3) permanent mold-casting, and (4) centrifugal-casting. Ferrous castings are produced in various types of stationary or centrifugal sand molds, while nonferrous metals are cast in either sand or metallic molds.

5–4. Sand-Casting. The most widely prevailing practice for producing ferrous castings is by the solidification of molten metal in molds made of green or wet sand or baked sand. In green or raw sand molding, the sand with the correct amount of binder is made cohesive with just sufficient water to facilitate molding and to maintain mold shape when the pattern is removed. The molds are soft and, consequently, allow considerable freedom for the contraction of the metal during cooling—an advantage when producing castings of intricate design and of unequal sections. The molds are also quickly available for continuous production methods, and much of the sand may be reclaimed and conditioned for further use. The principal disadvantage of green sand arises from its moisture content; the moisture, when driven out by the hot metal, produces gases that may become entrapped in the casting and cause defects or gas pockets. Escape of these gases must be facilitated by proper venting of the mold.

When castings with smoother surfaces and sharper image are required, the molding sand is compounded with a binder—such as cereal, rosin, or linseed oil—and the finished mold is baked until it is hard and all moisture is driven off. These molds must be made well in advance of the time they are required because of the necessary baking time. Baked sand molds resist erosion by the hot metal better than do those made of green sand, but their greater strength increases the possibility of shrinkage cracks or hot tears in the metal during the cooling period. Baking also increases mold costs.

A modified form of both green and baked sand-molding, which has proved of great advantage, is known as *skin-drying*. This method consists of spraying or facing green sand mold to a depth of about an inch with a mixture of green sand and a binder, such as wheat flour or similar material, and skin-drying with a torch or an electric plate. This is usually done just prior to pouring the metal.

5–5. Molding. Molds generally are made in a metal or wooden flask by ramming either natural or conditioned sand of suitable coarseness, permeability, moisture content, refractoriness, and bond around a pattern which, provided with the shrinkage allowance required for the various metals, conforms precisely in shape and dimensions to the desired casting. A small mold made on a molding bench is shown in Fig. 5–1. Flasks are square, rectangular, or round containers of a wide variety of dimensions and construction. They usually consist of two or three parts. A two-part flask consists of a lower half called *drag* and an upper half called *cope*. In a three-part flask the third part is called *cheek*. Flasks are made of either wood or metal. Wooden flasks are easily and cheaply made, are light in weight, and when necessary may be quickly adapted to requirements. Charring and rough handling, however, soon wear them out. Metal flasks are made of pressed sheet steel or cast aluminum alloy. Their higher initial cost is justified by their longer useful life.

For filling the molds with molten metal, one or more openings, called sprues, are provided which extend through the cope or upper half of the mold and are connected to the mold cavity by means of one or more gates. To assure the maximum flowability of the metal into the mold, sprues usually are made larger in area than the gates. To prevent the excessive accumulation of gases, molds must also be vented sufficiently to avoid possible explosions of molten metal or mold breakage by back pressure.

In recent years, molding operations formerly performed manually are now carried out extensively by mechanical means. The result has been higher production rates and more uniform castings. Particularly for repetitive production work, molds are made most frequently with the aid of various types of pneumatic molding machines, which either jolt, squeeze, or jar the sand into the mold to the proper hardness. Large molds are filled by stationary or portable mechanical sand-slingers, while vibrating machines loosen the pattern for easy removal. When sufficiently cool, the castings are shaken out of the molds mechanically, and the sand is likewise reconditioned or tempered for re-use.

When the molds required are too large to be conveniently manipulated on a molding bench, pits, or holes, are made in the molding shop floor, into which are placed baked sand cores that conform to the exterior and interior surfaces of the desired casting. Large castings may also be made in flasks on the foundry floor.

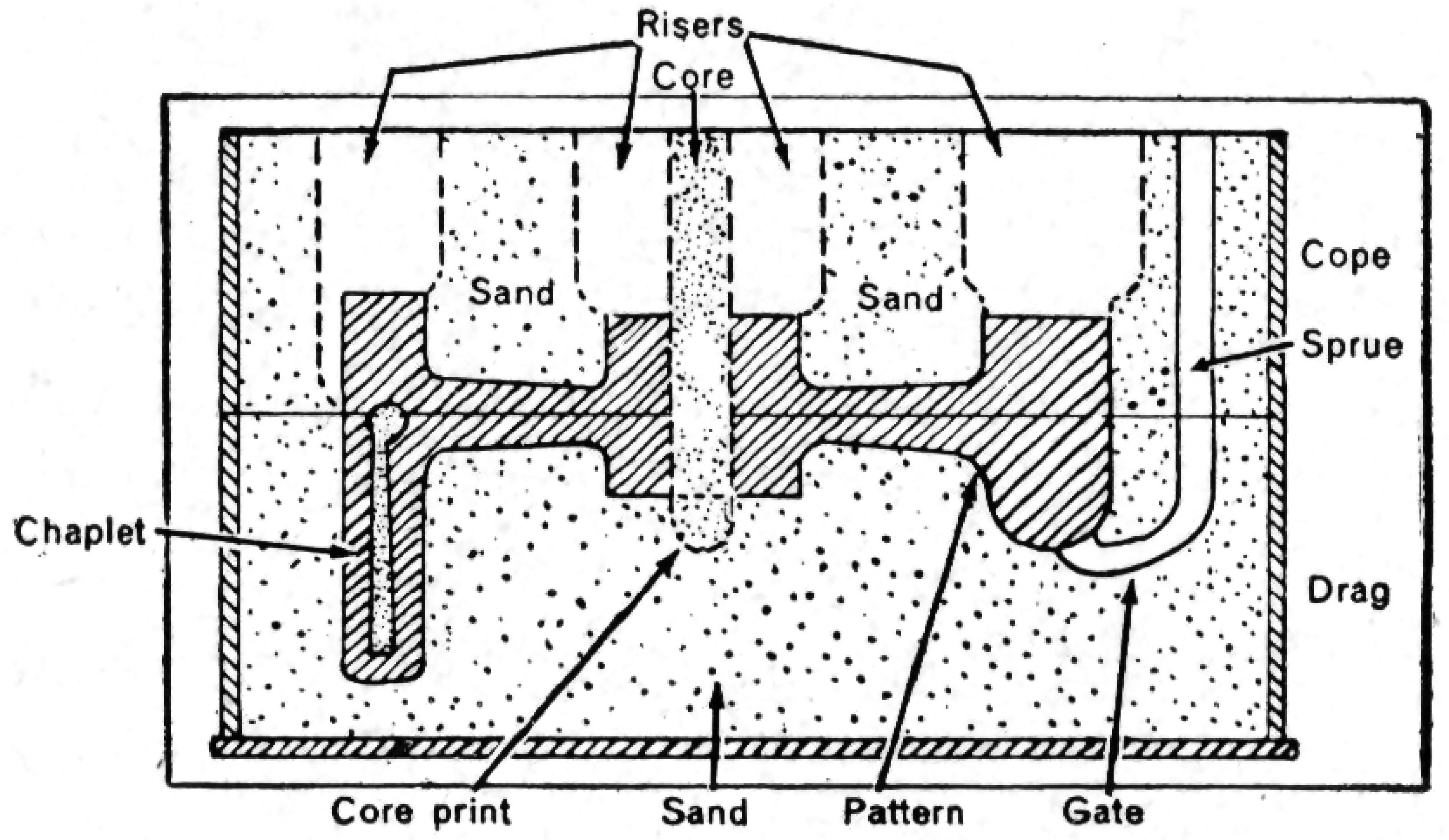

FIG. 5–1. Cross-section of small bench mold.

5–6. Cores. By means of cores, cavities or openings are provided in or through castings. Cores are also used to form the exterior surfaces of castings which cannot be molded in molding sand. By their insertion in appropriate places in a mold, such as in the hubs of large gears or flywheels, the volume of the metal throughout the casting may be equalized to assure more uniform cooling rates. A core is shown in position in Fig. 5–1. Cores are made of dry or green sand, loam, or metal. Core sand is mixed with a suitable binder, such as linseed oil, tung oil, soya bean oil, molasses, pitch, rosin, or cereal. The properties most desired in cores are strength to withstand weight and metal pressure, permeability to allow escape of gases, smoothness where they determine exterior surfaces, heat resistance, and collapsibility for easy withdrawal from the casting. To prevent their displacement by the metal, patterns are provided with projections called core prints, which form pockets or seats into which the cores fit after the pattern is removed. Core prints are shown in Fig. 5–1. The use of metal cores is limited to certain types of castings and to repetitive production work.

5–7. Materials for Patterns. *Wood.* Wood is ideally suited for patterns because of the ease by which patterns may be made therefrom and remade when alterations are necessary, and because of the light weight and relatively low initial cost of the wood. For large patterns, wood is invariably used. Its principal disadvantages are: unless the wood is thoroughly seasoned and dried, dimensional changes and warpage will result; and, when roughened and scratched by constant use under ordinary foundry working conditions, wood patterns are difficult to withdraw from the mold without disturbing or breaking it. White pine or sugar pine is the most commonly used for patterns, because it has good working characteristics, is close-grained, and takes a good coat of shellac or varnish. For more durable patterns, mahogany may be used.

Metal. For continuous use in the production of small castings, metal patterns are much favored over wood. The metal patterns withstand more severe handling, last longer, and retain their dimensions and shape better than wooden ones. They are, however, less easily altered when changes are necessary, and their cost is considerably higher. Metal patterns are usually cast from master patterns of wood, in which a double shrinkage allowance is necessary. Aluminum and magnesium alloys are used most frequently as pattern material because they are easy to machine, may be finished to a smooth surface, and are light to handle.

Types of Patterns. The design and materials selected for patterns are governed largely by the size, complexity, and number of castings required. In general, their construction conforms to a few specific types or standards, such as one-piece, multiple-piece, and gated patterns, and match plates.

One-piece patterns are usually small and simple and may be molded entirely in the drag.

Multiple-piece patterns may consist of two or more parts, snugly joined with wood or metal dowel pins. They are constructed so that they may be separated at some convenient parting line, in either the drag or the cope. Usually, but not always, the pattern has a straight parting line conforming to the parting line of the drag and cope parts of the flask.

Much molding time may be saved by attaching the requisite gates to the patterns so that the entire molding is completed in one operation without further handwork by the molder. These are called gated patterns and are used for comparatively small castings.

To simplify molding, to reduce molding costs, and to obtain more uniform castings, parts of a metal or wooden pattern may be mounted on the two flat surfaces of a metal or wooden plate with one part attached on the drag side and the other part on the cope side. This is known as a match plate.

If the two halves of the pattern are attached accurately opposite each other on either side of the plate, mismatching at the parting line of the casting will be avoided. In ramming the mold, the plate is first attached to the drag half of the flask and used as a follow board. Then the cope is similarly molded on the reverse side after the mold is turned upside down. When the molding is completed, the flask is parted and the pattern is removed leaving mold cavities and gates, formed by the two halves of the pattern, perfectly matched in the cope and the drag.

Pattern Colors. In order to enable the molder to tell which part or surface of a casting is to be machined or left in the "as-cast" condition, which parts constitute core prints, and which parts represent metal, the American Foundrymen's Association has adopted a system of standard colors by means of which the various surfaces and parts of a pattern can be easily identified. The colors used and their significance are as follows: all unfinished or unmachined surfaces are painted black; surfaces to be machined are painted red; core prints are painted yellow; seats for loose core prints are identified with red stripes on a yellow background; stop-offs are indicated by diagonal black stripes painted on a yellow base.

TABLE 5–1

APPROXIMATE SHRINKAGE ALLOWANCE FOR VARIOUS METALS

Metal	*Allowance In./Ft*
Aluminum	3/16
Cast-iron	1/8
Copper	3/16
Lead	5/16
Steel	1/4
Zinc	5/16

5–8. Shrinkage Allowance. To compensate for the dimensional shrinkage of metal castings as the solidified metal cools to ordinary temperatures, patterns must be made larger than the required castings by an amount which varies with (1) the type of metal; (2) size of casting; (3) pouring temperature; (4) complexity of casting; (5) design; and (6) size and shape of gates and risers. In making the patterns, patternmakers determine dimensions by use of a measuring scale, on which various shrinkage allowances are already made in the graduations. In general, the standard shrinkage allowances are as given in Table 5–1.

5–9. Die-Casting. The substitution of the term "dies" for molds, as used in the production of die-castings, does not imply that this form of casting is more nearly related to drop-forging, extrusion, or some other process in which dies are used than it is to other forms of casting. Die-casting is, fundamentally, a casting process and differs from other casting methods only in that (1) the molten or semimolten metal is forced into the mold (die) cavity under high pressure to produce accurately dimensioned parts and (2) the molds or dies are made of metal whose finished surfaces determine the shape of the castings. In attainable production rates, die-casting is comparable to stamping, drop-forging, and screw machine production of identical parts. While in some instances, permanent and sand molding are competitive with die-casting, the latter is incomparably faster than either of the other processes, besides having many other inherent advantages. The casting procedure involves forcing molten or semimolten metal into securely closed or locked dies under pressures varying from 350 to over 20,000 psi, as determined by the alloy, the casting temperature, and the size of the casting.

The process is adapted to the production of small and even intricate parts with close dimensional tolerances and excellent surface finish. Because of the strength of the metal and the possibility of casting very thin sections, a reduction of weight and a saving of metal are effected also.

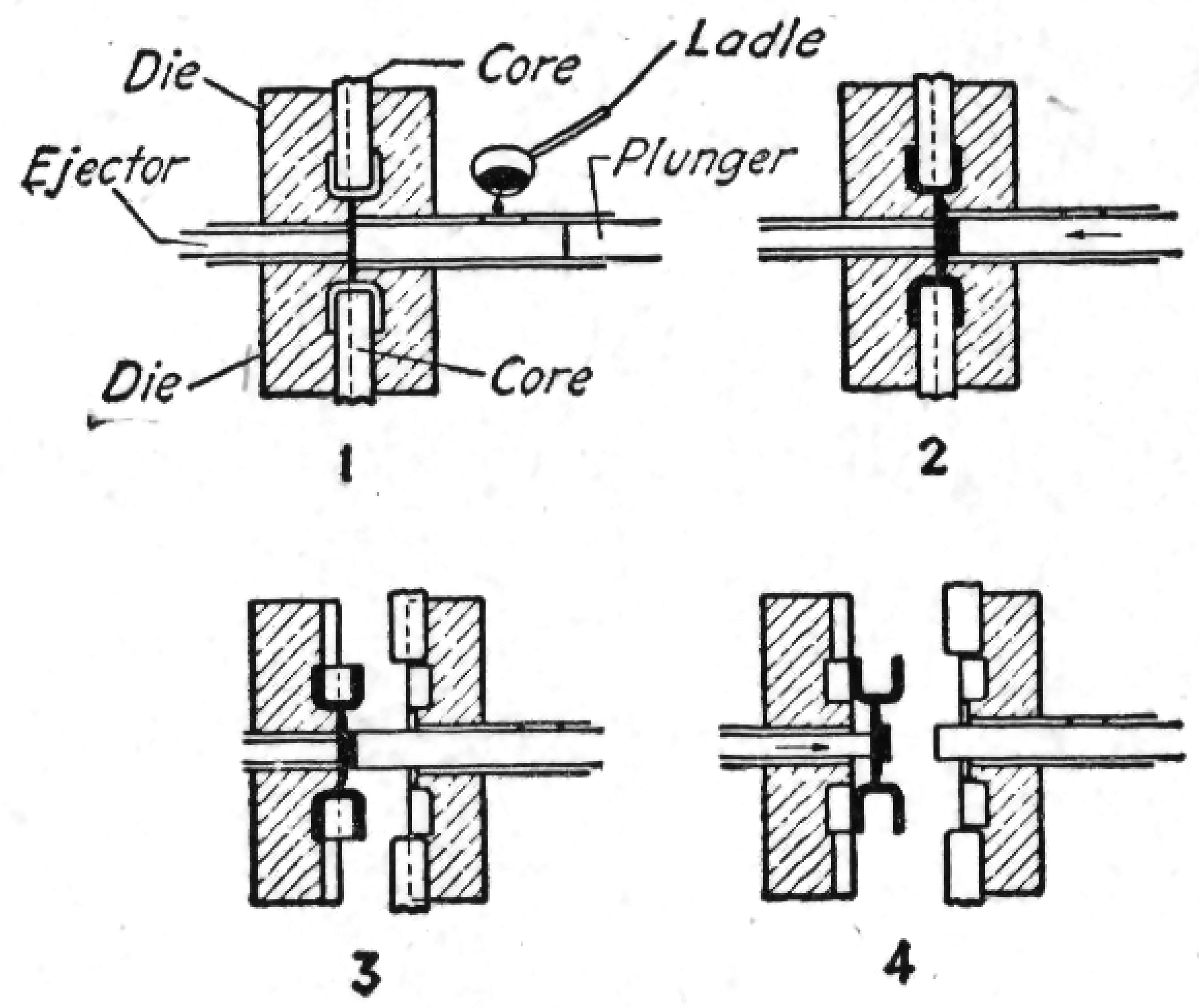

FIG. 5–2 Diagram illustrating four stages in production of pair of cup-shaped brass die-castings in cold chamber machine having horizontal plunger.

In most instances, machining operations may be eliminated entirely. Where necessary to embody holes or openings or undercuts, metal cores or pins and slides may be incorporated as integral or supplemental parts of the dies and then be withdrawn either when the die is opened or after. The application of cores is shown in Fig. 5–2: 1, ladling metal into cold chamber; 2, molten metal after it is forced into die; 3, cores withdrawn, die opened, and plunger advanced to eject casting from fixed half of die; 4, plunger withdrawn and ejector advanced to force gate of castings from ejector half of die.

In this manner, the need for drilling operations is minimized or eliminated altogether. Typical die-castings are auto carburetors, camera parts, automobile body parts, fuel pumps, grilles, washing machine parts, small pulleys and fans, business machine and vacuum cleaner parts, vending machines, etc.

5–10. Die-Casting Alloys. Metals constituting the base for die-casting alloys, in the order of their commercial use, are: (a) zinc, (b) alu-

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TABLE 5–2

COMPARISON OF DESIRABLE PROPERTIES OF THREE DIE-CASTING ALLOYS

SELECTION FACTOR		ZINC ALLOYS ASTM NOS. 21, 23, 25	ALUMINUM ALLOYS ASTM NOS. 85, SC2	MAGNESIUM ALLOYS ASTM NOS. 12, 13
MECHANICAL PROPERTIES	Tensile Strength	1 (strongest)	2	3
	Impact Strength	1 (toughest)	2	2
	Elongation	1 (most ductile)	2	2
	Dimensional Stability	2*	(1 most stable)	2
	Resistance to Cold Flow	2	1	1
	Brinell Hardness	1 (hardest)	2	2
PHYSICAL CONSTANTS	Electrical Conductivity	2	1 (highest)	3
	Thermal Conductivity	2	1 (highest)	3
	Melting Point‖	1 (lowest)	2	2
	Weight, per cu. in.	3	2	1 (lightest)
CASTING CHARACTERISTICS	Ease, Speed of Casting	1 (easiest)	2	2
	Maximum Feasible Size	1 (greatest)	2	3
	Complexity of Shape	1 (most complex)	2	3
	Dimensional Accuracy	1 (most accurate)	2	2
	Minimum Section Thickness	1 (thinnest)	2	2
	Surface Smoothness	1 (smoothest)	2	2
COST	Die Cost†	1 (lowest)	2	2
	Production Cost	1 (lowest)	2	2
	Machining Cost	1	2	1
	Finishing Cost‡	1 (lowest)	2	2
	Cost per Piece§	1 (lowest)	2	2
EXTENT OF USE		1 (most used)	2	3

* Through the use of a low temperature annealing treatment, Alloy No. 23 can be made virtually stable in dimensions.

‖ A low melting point is favorable in reducing die cost and upkeep and facilitates casting.

† Dies for casting the low melting point alloys are least expensive and have longest life.

‡ Includes polishing and buffing expense as well as ease of applying all types of commercial finishes, both electrodeposited and organic.

§ Based on die and fuel costs, production speed and machining and finishing costs.

From Designing for Die-Casting, *New Jersey Zinc Co. (1945 ed.)*

minum, (c) magnesium, (d) copper, (e) lead, and (f) tin. The first four alloys account for approximately 90 per cent of all die-casting alloys; a comparison based on some of their desirable properties is given in Table 5–2.

The proper selection of a die-casting alloy necessitates consideration of many factors, involving economics as well as mechanical or chemical properties and uses. No alloy is universally satisfactory for all purposes. For comparison, a brief summary of the principal characteristics of the different base metals and their applications is given below.

5–11. Zinc Alloys. Die-castings with zinc constituting the base metal have the widest commercial applications of all die-casting alloys. Some of the reasons for this are that they are comparatively low in initial cost per pound of casting; are easy to cast; have a low melting point (about 700F) and thus minimize fuel cost, die cost, and maintenance; have low solidification shrinkage, which permits the casting of complex shapes without undue shrinkage tears; have higher tensile strength than other alloys, except those of copper; may be cast to extremely close dimensional tolerances; have fair corrosion resistance for most applications; are easy to machine; may be given almost any type of surface finish by electrodeposition of chromium, nickel, copper, brass, or bronze, or by painting with enamels, lacquers, or varnishes.

Their disadvantages are that practically pure zinc (99.99 per cent) must be used as a base metal to avoid dimensional changes; and contamination of the alloy by lead, tin, or cadmium produces intergranular corrosion due to a strong galvanic action caused by the electrical potential differences of these metals. Also, because of their low melting point, the castings should not be used at operating temperatures exceeding 350F. Zinc is readily attacked by alkalies, soaps, and weak solutions of nitric or sulphuric or hydrochloric acids.

The compositions and properties of representative zinc-base, die-casting alloys are given in Table 5–3.

5–12. Aluminum Alloys. One of the primary advantages of the aluminum-base alloys is their high weight-strength ratio, which makes them adaptable for a wide variety of applications. They also have good to excellent corrosion resistance, depending on conditions; for example, because of their high resistance to salt water corrosion, some of these alloys are extensively used for aircraft engine parts and marine fittings. They may be used where temperatures are higher than are feasible for zinc alloys. The alloys also have excellent flow characteristics, which enable them to be cast into very thin walled and intricate parts. They take and retain a high polish and resist tarnish for a longer time than the zinc alloys. Except for iron, they are generally not much affected by small amounts of other impurities. They have excellent thermal and electrical

TABLE 5–3

Composition and Properties of Zinc Alloys for Die-Casting

DESIGNATION	ASTM	XXI	XXIII	XXV
	SAE	921	903	925
	The New Jersey Zinc Company	Zamak-2	Zamak-3	Zamak-5
COMPOSITION[*] % BY WEIGHT	Copper	2.5 to 3.5	.10 max.	.75 to 1.25
	Aluminum	3.5 to 4.5	3.5 to 4.3	3.5 to 4.3
	Magnesium	.02 to .10	.03 to .08	.03 to .08
	Iron max.	.100	.100	.100
	Lead max.	.007	.007	.007
	Cadmium max.	.005	.005	.005
	Tin max.	.005	.005	.005
	Zinc (99.99+% purity)	Remainder	Remainder	Remainder
MECHANICAL[†] PROPERTIES	Charpy Impact Strength, ft.lb., ¼x¼-in. bar, as cast	35	43	48
	Charpy Impact Strength, ft.lb., ¼x¼-in. bar, after 7 yrs. indoor aging	7	41	42
	Tensile Strength psi as cast	52,100	41,000	47,600
	Tensile Strength psi after 7 years indoor aging	48,100	33,800	38,300
	Elongation % in 2 in. as cast	8	10	7
	Elongation % in 2 in. after 7 years indoor aging	5	16	15
	Expansion (growth) inches per inch after 7 years indoor aging	.0055	.0006	.0004
OTHER PROPERTIES[†] AND CONSTANTS (AS CAST)	Brinell Hardness	100	82	91
	Compression Strength—Lb./Sq. In.	93,000	60,000	87,000
	Electrical Conductivity—Mhos./cm. cube at 20°C.	146,000	157,000	153,000
	Melting Point—°C.	379.5	380.9	380.6
	Melting Point—°F.	715.1	717.6	717.1
	Modulus of Rupture—Lb./Sq. In.	116,000	95,000	105,000
	Shearing Strength—Lb./Sq. In.	46,000	31,000	38,000
	Solidification Point—°C.	379.3	380.6	380.4
	Solidification Point—°F.	714.7	717.1	716.7
	Solidification Shrinkage—Inch/Foot	.15	.14	.14
	Specific Gravity	6.7	6.6	6.7
	Specific Heat—cal./gm./°C.	.10	.10	.10
	Thermal Conductivity—cal./Sec./sq. cm./cm./°C. at 18°C.	.25	.27	.26
	Thermal Expansion per °C.	.0000277	.0000274	.0000274
	Thermal Expansion per °F.	.0000154	.0000152	.0000152
	Transverse Deflection—In.	.22	.27	.16
	Weight (Lb.)/Cubic Inch	.24	.24	.24

[*] Composition as provided in ASTM and SAE specifications. The Zamak alloys meet these specifications but are held within closer tolerances.

[†] Properties and constants are as determined on Zamak alloys by The New Jersey Zinc Company. Values for impact strength, tensile strength and elongation, as cast, are well above the minimum ASTM and SAE requirements.

From Designing for Die-Casting, *New Jersey Zinc Co.* (*1945 ed.*)

conductivity and may be used when direct contact with food is involved. Their ductility is somewhat lower than that of the zinc alloys.

The principal disadvantage of these alloys is their relatively high melting point and consequently high casting temperature, which necessitates the use of more expensive heat-treated alloy steel dies than are required for the alloys of lower melting points. High casting temperature results in higher die maintenance costs and more frequent die changes. The higher temperature also leads to greater solidification shrinkage, longer cooling time, and lower production rates. As will be pointed out later, die-casting procedures employed in the production of other alloys are unsuited for these alloys, since iron in contact with the molten aluminum is attacked and dissolves in the alloy. The resulting contamination tends to reduce the mechanical properties of the casting and causes rapid deterioration of the machine parts.

The composition and properties of aluminum-base, die-casting alloys are given in Table 5–4.

5–13. Magnesium Alloys. Die-castings of magnesium-base alloys are comparable to the aluminum-base alloys in casting temperatures, mechanical properties, and casting techniques. Since they are the lightest in weight of all cast metals, they are superior to the aluminum alloys in their weight-strength ratio and have a higher machinability rating than any other die-cast alloys. As shown in Table 5–5, the alloys melt at about 1100–1120F, a temperature which imposes the same restriction on the use of steel for dies as that of the aluminum alloys. Because of rather poor resistance to corrosion in moist air and salt sprays, alloys of magnesium subjected to these conditions must be amply protected by suitable inhibiting priming coats after casting, as well as by plated coatings such as nickel or chromium or organic finishes. Precautions must also be taken to avoid oxidation or burning and other hazards involved in melting the alloy, and suitable coolants must be used to avoid ignition of the chips in machining operations. Magnesium-base alloys respond to solution heat treatment with higher impact strength but slightly reduced yield strength. Their composition and properties are given in Table 5–5.

5–14. Copper Alloys. Die-castings of copper-base alloys possess tensile and yield strengths equal to those of medium-carbon steels. They are also superior in impact strength to sand-cast alloys of the same composition. The alloys are used extensively where high strength and corrosion resistance are needed. In spite of excellent properties, only a small percentage of the total tonnage of die-castings is composed of copper-base alloys. This is attributed to: the increased cost of production caused by the influence of their high casting temperature (1575–1675F), which necessitates the use of alloy steel dies to resist wear and checking; their relatively low production rates; and the more expensive equipment necessary

TABLE 5–4

Composition and Properties of Aluminum Alloys for Die-Casting

DESIGNATION									
ASTM	S4	S5	S9	SC2	SC5	SC6	SC7	—	—
SAE	304	305	—	—	—	—	—	—	—
Aluminum Co. of Am. (Alcoa)	43	13	—	85	—	A380	380	218	360
COMPOSITION %*									
Copper	.6 max.	.6 max.	.6 max.	3.0-4.0	3.0-4.0	3.0-4.0	3.0-4.0	.2 max.	.6 max.
Silicon	4.5-6.0	11.0-13.0	11.0-13.0	4.5-5.5	4.5-5.5	7.5-9.5	7.5-9.5	.3 max.	9.0-10.0
Iron max.	2.0	2.0	1.3	2.0	1.3	1.3	2.0	1.8	2.0
Magnesium max.	.1 max.	.1 max.	.1 max.	.1 max.	.1 max.	.1 max.	.1 max.	7.5-8.5	.4-.6
Manganese	.3	.3	.3	.5	.5	.5	.5	.3	.3
Zinc max.	.5	.5	.5	1.0	.6	.6	1.0	.1	.5
Nickel	.5 max.	.5 max.	.5 max.	.5 max.	.5 max.	.5 max.	.5 max.	.1 max.	.5 max.
Tin max.	.1	.1	.1	.3	.3	.3	.3	.1	.1
Total other Impurities max.	.2	.2	.2	.5	.5	.5	.5	.2	.2
PROPERTIES AND CONSTANTS									
Yield Strength, Tension (Set 0.2%) psi	14,000	18,000	—	22,000	20,000	23,000	25,000	23,000	23,000
Ultimate Tensile Strength psi	30,000	37,000	35,000	38,000	35,000	41,000	43,000	42,000	42,000
Elongation, % in 2 in.	5.0	1.8	3.5	2.5	3.0	3.0	2.0	7.0	1.8
Charpy Impact, ft.lb. ¼x¼ in. bar	4.5	2.0	—	2.5	3.0	3.5	3.2	10.0	—
Specific Gravity	2.70	2.66	2.66	2.78	2.78	2.76	2.76	2.53	2.68
Weight lb. per cu. in.	.097	.096	.096	.101	.101	.099	.099	.091	.097
Shearing Strength psi	21,000	26,000	24,000	26,000	24,000	29,000	30,000	29,000	29,000
Melting Point (Liquid temp.) °F	1,165	1,065	1,065	1,145	1,145	1,090	1,090	1,160	1,110
Thermal Conductivity CGS Units	.34	.37	.37	.27	.28	.28	.26	.24	.35
Thermal Expansion in./in./°C	.000022	.000020	.000020	.000021	.000021	.000020	.000020	.000024	.000021
Electrical Resistivity microhm.-cm	4.8	4.4	4.4	6.2	5.9	5.9	6.5	7.1	4.7

*Correspond with ASTM specifications in the case of ASTM standard alloys. In other cases compositions are as given by Aluminum Company of America. The Aluminum Company of America is the source for the above data, and has provided the following information concerning these data: The composition limits given are from ASTM Specification B85-44T except for alloys 218 and 360, which are Alcoa alloys. To the extent that the data are included in the ASTM specification, the mechanical properties were secured from that source. The other mechanical properties are from Alcoa tests or were estimated from available data; the shear strengths, for example, being calculated as about 70% of the tensile strength, which appears to be a good average ratio. The physical properties generally were arrived at by calculations based on an "average" composition and the assumption of reasonably sound castings: in some cases, they were estimated from test results on alloys of similar, but not identical, compositions. Hardness values have not been included not only because of the limited data available, but also because of the inherent variation of this property in any casting.

From Designing for Die-Casting, *New Jersey Zinc Co.* (*1945 ed.*)

TABLE 5–5

Composition and Properties of Magnesium Alloys for Die-Casting

DESIGNATION	ASTM	No. 12	No. 13
	SAE	—	501
	Dow Chemical Co.	Dowmetal K	Dowmetal R
	American Magnesium Corp.	AM 230	AM 263
COMPOSITION %*	Aluminum	9.0 to 11.0	8.3 to 9.7
	Manganese min.	.10	.13
	Zinc	.3 max.	.4 to 1.0
	Silicon max.	1.0	.5
	Copper max.	.05	.05
	Nickel max.	.03	.03
	Magnesium	Remainder	Remainder
PROPERTIES AND CONSTANTS†	Tensile Strength, psi	30,000	33,000
	Yield Strength, psi	22,000	22,000
	Elongation % in 2 in.	1	3
	Brinell Hardness	62	60
	Izod Impact Strength, ft.lb.	1	2
	Specific Gravity	1.81	1.81
	Weight per cu. in.	.066	.066
	Melting Point °F.	1100	1120

* **Composition of alloys as in ASTM Specification.**

† **Properties, as in data furnished by The Dow Chemical Company and by American Magnesium Corporation.**

From Designing for Die-Casting, *New Jersey Zinc Co. (1945 ed.)*

TABLE 5–6

Composition and Properties of Copper Alloys for Die-Casting

Common Name of Alloy	Yellow Brass*	Doler Brass No. 1	Doler Brass No. 4 "Brastil"	Doler Brass No. 5	Tinicosil	Manganese Bronze*
Composition (per cent):						
Copper	57–59	65.0	81.5	83.0	42.0	55–60
Zinc	40–42	Rem.	Rem.	Rem.	41.0	38–42
Tin	1.5 max.	0.25 max.	0.10 max.	0.25 max.	......	1.5 max.
Aluminum	0.1 max.	0.25 max.	0.05 max.	1.0	......	1.5 max.
Lead	0.40 max.	0.25 max.	0.25 max.	0.25 max.	1.0	0.40 max.
Manganese	0.0–0.25	0.25 max.	0.25 max.	1.0	......	3.5 max.
Nickel	......	0.25 max.	0.25 max.	0.25 max.	16.0	......
Silicon	......	1.0	4.0	5.0	......	......
Iron	2.0 max.	0.25 max.	0.15 max.	0.25 max.	......	2.0 max.
Other impurities	......	0.25 max.	0.25 max.	0.25 max.	......	......
Properties and constants:						
Ultimate tensile strength, psi	65,000	65,000	85,000	105,000	85,000	65,000
Yield point, psi	40,000	35,000	50,000	60,000	65,000 to 72,000	30,000
Impact strength, Charpy, ft lb	33	36	36	30	......	36
Elongation, per cent in 2 in	15.0	25.0	8.00	5.0	15.0	10.0
Reduction of area, per cent	15–20	......	10–15	......	10–18	......
Brinell hardness No.	120–130	120	170	190	160	110–130
Specific gravity	8.5	8.6	8.3	8.2	8.5	......
Weight per cu in.	0.305	0.308	0.297	0.295	0.305	......
Melting point, F	1650	1575	1575	1564	1675	1650
Solidification shrinkage, in. per ft	3/16	......	3/16	......	3/16	......
Machinability	Fair	Good	Fair	Fair	Good	Fair
Corrosion resistance	Good	Good	High	High	High	Good

* Both these alloys come within SAE No. 43 tolerances as to composition.

TABLE 5-7

COMPOSITION AND PROPERTIES OF LEAD ALLOYS FOR DIE-CASTING

ASTM Designation	No. 4	No. 5	Bearing Alloy	"C.T." Metal	Tin-Free Alloy
Composition (per cent):					
Lead	79–81	89–91	80	85–87	90
Tin	4–6	......	5	0.65	......
Antimony	14–16	9.25–10.75	15	12.50	10
Copper, max.	0.50	0.50	0.50	......	0.50
Arsenic, max.	0.15	0.15	0.20	0.65	0.25
Zinc, max.	0.01	0.01	......	......	......
Aluminum, max.	0.01	0.01	......	......	......
Properties and constants:					
Tensile strength, psi	13,800	12,500	9,100	9,800	7,700
Impact strength, Izod, ft lb	0.6	0.4	0.8	0.2	0.8
Elongation, per cent in 2 in.	10.5	2.0	3.8	5.5	15.5
Brinell hardness	23.2	24.1	23.2	18.0	15.5
Specific gravity	10.24	9.73	10.12	10.38	10.65
Weight, lb cu in.	0.370	0.351	0.365	0.379	0.384
Melting range, F	459–493	464–514	462–500	473–504	473–498
Solidification shrinkage, in./in.	0.002	......	......	......	......
Corrosion resistance	Good	Good	Good	Good	Good
Bearing qualities	Good	Good	Good	Fair	Fair

to withstand the high pressures of about 20,000 psi, which are required to force the metal into the mold and to hold the dies securely closed. Copper-base die-castings cannot be produced economically to conform to the narrow limits possible with other alloys; and, in general, they comprise only small castings. Some of the alloys may be welded and all of them may be soft- and hard-soldered. They have good machinability. Their compositions and properties are given in Table 5–6.

5–15. Lead- and Tin-Base Alloys. These alloys find somewhat limited applications because of the better mechanical properties of the zinc alloys, which are often produced at lower cost than the lead and tin alloys and have equal castability. Because of their high corrosion resistance, the lead alloys are adapted for use in contact with corrosive chemicals; and their density makes them suitable for use in X-ray equipment. For bearings and similar uses where hardness is desirable, antimony and tin with small amounts of copper are added to the lead.

TABLE 5–8

COMPOSITION AND PROPERTIES OF TIN ALLOYS FOR DIE-CASTING

ASTM Designation	No. 1	No. 2	No. 3
Composition (per cent):			
Tin	90–92	80–84	64–66
Antimony	4–5	12–14	14–16
Lead	0.35 max.	0.35 max.	17–19
Copper, max.	4–5	4–6	1.5–2.5
Iron, max.	0.08	0.08	0.08
Arsenic, max.	0.08	0.08	0.15
Zinc, max.	0.01	0.01	0.01
Aluminum, max.	0.01	0.01	0.01
Properties and constants:			
Tensile strength, psi	9,000	10,000	7,800
Elongation, per cent in 2 in.	2	1	1.25
Brinell hardness	23–26	30	27.7
Specific gravity	7.40	7.53	7.98
Weight, lb per cu in.	0.266	0.27	0.287
Melting point, F	400	400	400
Casting temperature, F	700	760	700
Solidification shrinkage, in./in.	0.002–0.003	0.002–0.003	......
Corrosion resistance	High	High	High
Bearing qualities	Excellent	Excellent	Good

Tin-base alloys are higher in cost than the lead-base alloys, while their mechanical properties are quite similar. Their casting temperature is slightly higher than that of the lead alloys and about the same as that of the zinc alloys. These castings may be used as parts of equipment for preparation of foods and beverages, and they may be cast with very narrow limits and into small parts. (As shown by Tables 5–8, antimony is the principal alloy.)

The compositions and properties of lead- and tin-base die-casting alloys are given in Tables 5–7 and 5 8.

5–16. Die Design. In addition to a knowledge of fundamental principles, the development of dies for the economical and practical production of closely dimensioned parts also requires considerable experimental work, before the dies are actually put in service. While basically similar, nearly all dies have some variables or features not embodied in other dies, and the effects of these are difficult to predict and provide for beforehand.

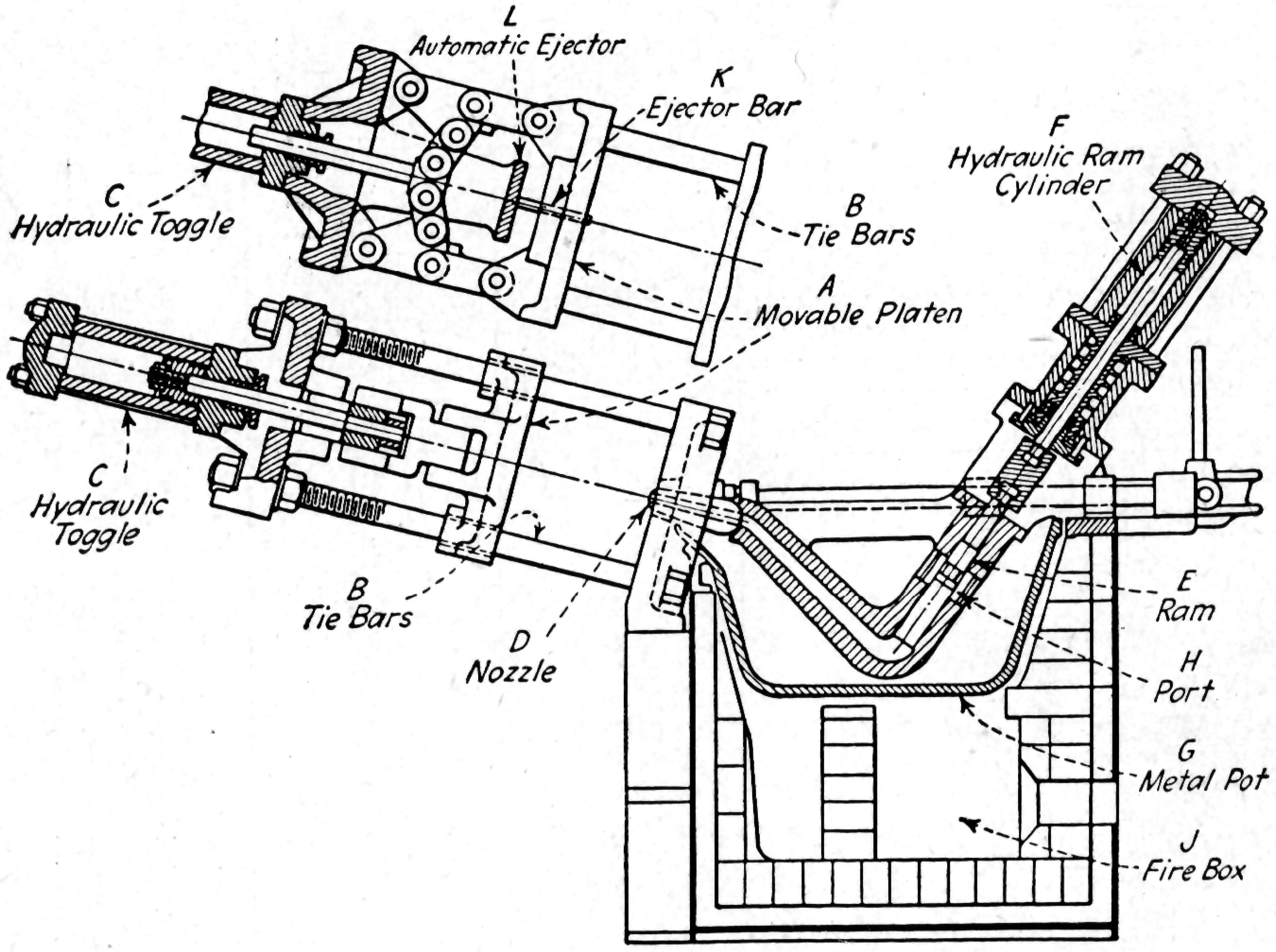

FIG. 5–3. Section through modern machine for die-casting zinc alloy, equipped with hydraulically operated plunger set at an angle.

Dies for die-casting are comparable to those employed in plastic-molding or in sand-casting, in that they comprise two or more parts or sections. These parts are separated at a parting line, preferably a plane surface, although it is often necessary to part on an irregular surface. In modern die-casting machines, the parting is in a vertical or slightly inclined plane, as shown in Fig. 5–3. One half of the die is attached to the stationary platen of the machine on the side next to the metal pot or cold chamber, while the other half is fixed to the movable cover portion, which usually contains the large portion of the die cavity.

The many intricacies of die design cannot be discussed in detail in this text; and, therefore, only the more fundamental and desirable aspects will be pointed out.

Where large quantities of parts of favorable shape and size are required, the dies may be constructed with a number of cavities connected by suitable gates. This construction provides for increased production if the machine capacity is sufficient to fill all cavities readily. Examples of multiple-cavity dies are shown in Fig. 5–4 and Fig. 5–5.

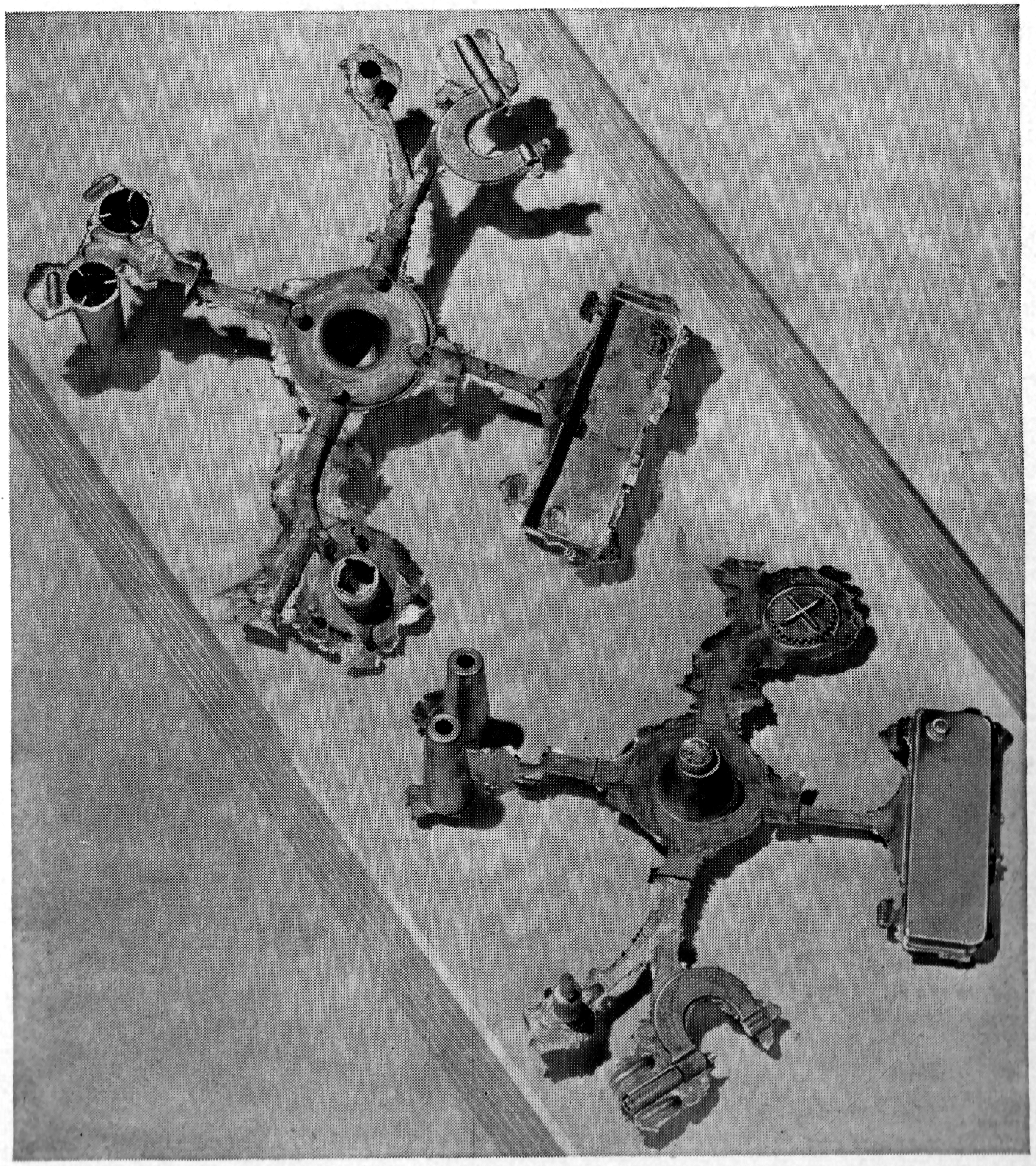

FIG. 5–4. Examples of use of multiple-cavity dies in die-casting. (Courtesy of New Jersey Zinc Co.)

To avoid air pressures within the mold and consequent underfilling of cavities, or gas pockets in the metal, vents must be provided so that the air may escape. These vents are usually provided at the parting line as small slots. Some air also escapes around the slides and metal cores. The dimensions of these vents must be kept to the necessary minimum so that the amount of molten metal, which naturally follows the air, freezes quickly and does not constitute too much flash to cut off.

In conformity with good practice, ample fillets and radii should be provided to avoid shrinkage tears and high stress-concentration areas.

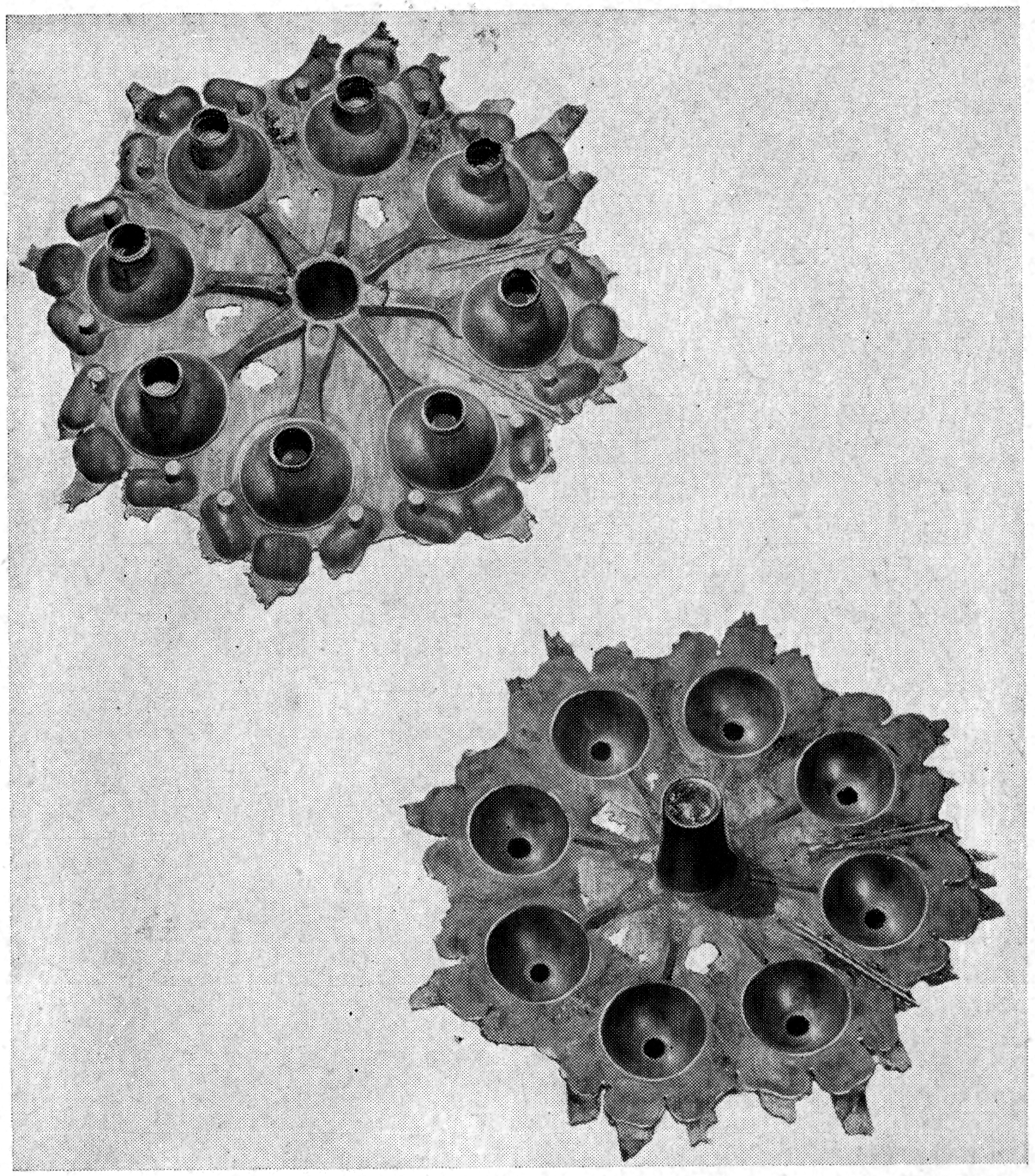

Fig. 5–5. Multiple-mold dies. (Courtesy of New Jersey Zinc Co.)

Balanced sections with avoidance of deep boxlike cavities which cannot be plated or buffed are also desirable features. Both internal and external undercuts, which require slides and movable cores, should also be eliminated as far as possible, since they add to the complexity of the die and increase die cost, and ultimately product cost.

It is practical in some instances to have but one cavity in the die and to produce a single casting at each shot or machine movement. In order

TABLE 5–9

Approximate Composition of Steels for Dies for Die-Castings*

Steel No.	C	Mn	Si	W	Cr	V	Mo	
2	0.45	0.70			0.80			Ni-1.25
	Used for Zn, Sn, and Pb base alloys – not heat treated for Pb and Sn, but sometimes heat treated for Zn.							
3	0.30	0.50			1.20		0.50 max.	Al-1.20
	Used for Zn, Pb base alloys – preferably in nitrided condition.							
4	0.45	0.60			2.25	0.20 Opt.		
	Used for some long run dies on Zn. Becoming obsolete for Al and Mg – heat treated.							
5	0.35		0.90	4.50	5.25	0.25 Opt.	0.50 Opt.	Ni-0.50 Opt. Co-0.50 Opt.
	Used heat treated – used for Al and Mg base alloys but is giving way to No. 6 and No. 7.							
6	0.30	0.60	0.90		5.00	0.25 Opt.	1.00	
	Used for Al and Mg base alloys – heat treated.							
7	0.30		0.90	1.00	5.00	0.25 Opt.	1.00	Co-0.50 Opt.
	Used for Al and Mg base alloys – heat treated.							
8	0.35			10.00	3.00	0.50		
	Used for Cu base alloys – heat treated.							

*The analyses given are type analyses only. Actual analyses of the steel they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

From Die-Casting for Engineers, *New Jersey Zinc Co. (1945 ed.)*

to utilize fully the die dimensions and to increase production at reduced costs, multiple-cavity dies should, whenever possible, be used.

5–17. Steels for Die-Casting Dies. The selection of suitable steel for dies is based on several considerations, among which may be mentioned (1) the number of castings required; (2) the intricacy of the casting, (3) the characteristics of the casting alloy; and (4) the casting temperature. In addition to these must be added the comparative costs of various steels, their machinability, and the possible necessity of heat treatment.

The properties most desirable in die steels are high resistance to wear or erosion, resistance to heat checking or cracking when in contact with the molten alloy, retention of shape and dimensions under high pressures and heavy battering, and resistance to excessive tempering or softening at operating temperatures.

For the casting of the low melting alloys, no great problem arises, since any low or medium plain carbon steel is satisfactory without any heat treatment. For the aluminum, magnesium, and copper alloys, only heat-treated alloy steels will be satisfactory under the more severe conditions imposed by the higher temperatures and pressures.

In Table 5–9, there is suggested the approximate composition of steels of various types suitable for the different casting alloys.

5–18. Die-Casting Machines. In mechanical features and production capacities, die-casting machines vary widely in appearance and design, from those operated manually for the production of simple castings of low melting alloys, to those designed for the casting of more complicated parts of high melting alloys and operated either hydraulically or pneumatically. In these latter machines, all movements are performed automatically and in proper sequence at preselected time intervals. The principal functions of these machines are: to securely close and open the dies, to force the right amount of metal into the die cavities, to eject the casting, and to operate all slides and cores in and out of the mold cavities. The machines designed for casting low melting alloys also include a heated crucible for melting the alloy to be cast or for holding the metal at the temperature required for casting, after preheating in a separate furnace. The aluminum-, magnesium-, and copper-base alloys are cast in cold chamber machines, as shown in Fig. 5–6, into which sufficient metal for one "shot" is ladled from a furnace, which is not an integral part of the casting machine. By shortening the time that the functioning parts of the machine contact the alloy, this procedure reduces the tendency to erosion, wear, and heat checking or cracking of the parts.

The principal functions of these machines, described above, are similar and require for their performance the employment of basic mechanical principles; yet, nearly all machines embody features which are individual and unique. This is because nearly all large producers of die-castings design and build machines adapted to their needs. Only in the broader sense, therefore, may a description be given here.

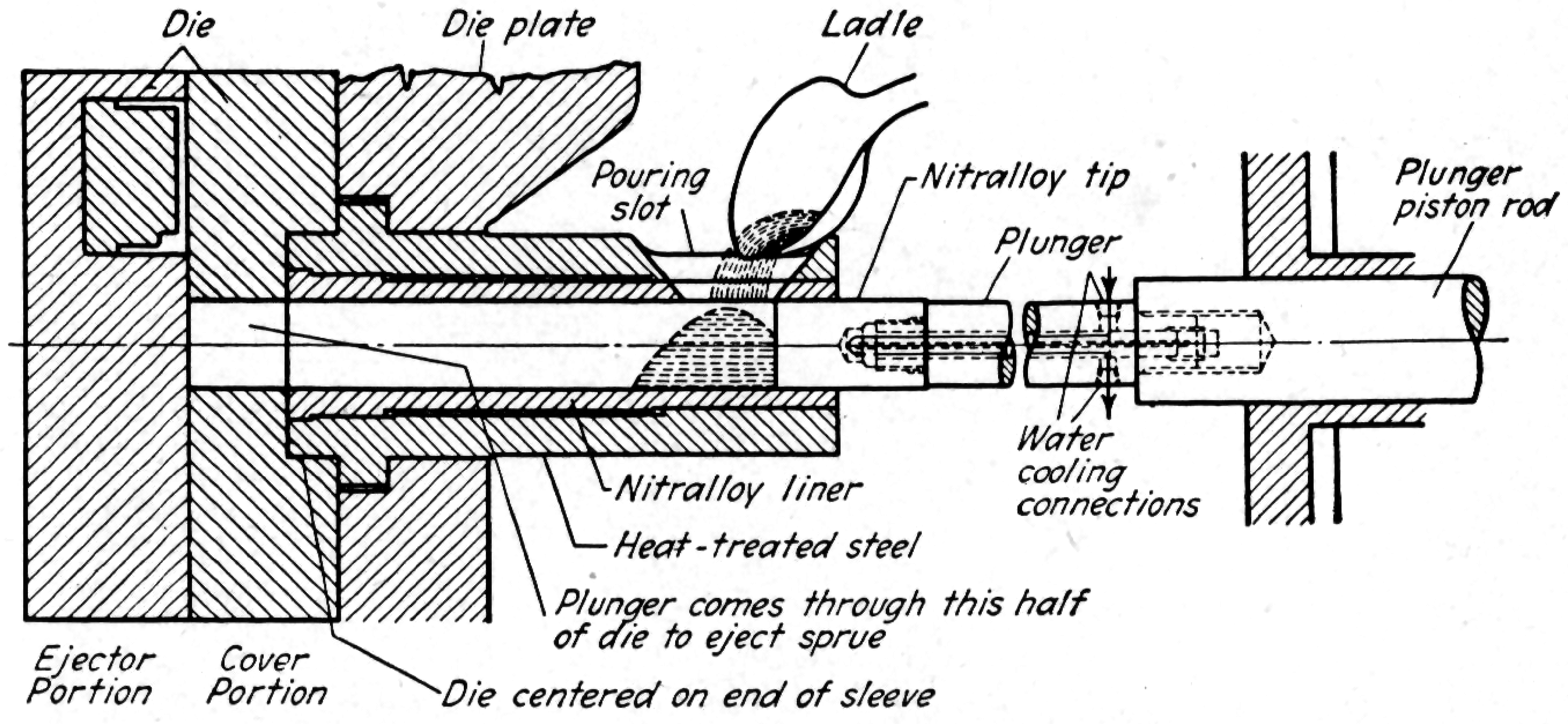

FIG. 5–6. Sectioned diagram showing die, cold chamber, and horizontal ram or plunger (in charging position) of modern cold chamber type of die-casting machine.

In general, die-castings are made by machines in which a plunger or piston, operated by hydraulic or pneumatic pressure, forces the molten metal from a cylinder into the die cavities, or by simpler machines in which the dies are filled by direct air pressure.

Fig. 5–7 shows a section of a modern die-casting machine with a vertical ram or piston actuated by air pressure. Fig. 5–3 shows a machine in which the operating plunger is set at an angle and is hydraulically operated. In both types of machines the molten metal enters the cylinder at ports, as shown, and is forced through a sprue into the die. Zinc-, tin-, and lead-base castings are produced in these machines at pressures ranging from between 350 and 5,000 psi. Although the higher pressures are beneficial in producing more sharply outlined castings and denser structures, pressures of from 1,000 to 1,500 psi are most commonly used.

Cold chamber machines for the casting of copper, aluminum, and magnesium alloys are similar to the continuous die-casting machines in the mechanical operations of the dies and auxiliary equipment. They differ in that pressures of 6,000 to over 20,000 psi are required, the heating chamber is separate from the casting machine, and greater strength and heavier parts are required because of the higher pressures. A cold chamber machine with a horizontal ram in charging position is shown in Fig. 5–6.

Machines which depend on direct external air pressure for filling the dies are provided with a pressure chamber which, because of its shape, is called a gooseneck. This unit is submerged below the level of the molten metal so as to take up a sufficient amount of metal; the unit is then elevated until its nozzle aligns with the sprue in the dies. When the dies are closed securely, an air valve is opened; and the metal in the gooseneck is transferred into the die cavity under pressure. A significant feature of this type of machine is that the gooseneck is not in contact with the molten alloy except when ready to "shoot" or fill the dies. For this reason the machine is adapted to the casting of aluminum alloys and pure zinc which, when in continuous contact at their respective high melting temperatures, readily attack the iron and destroy the close fits of the piston and cylinder in the plunger type machines.

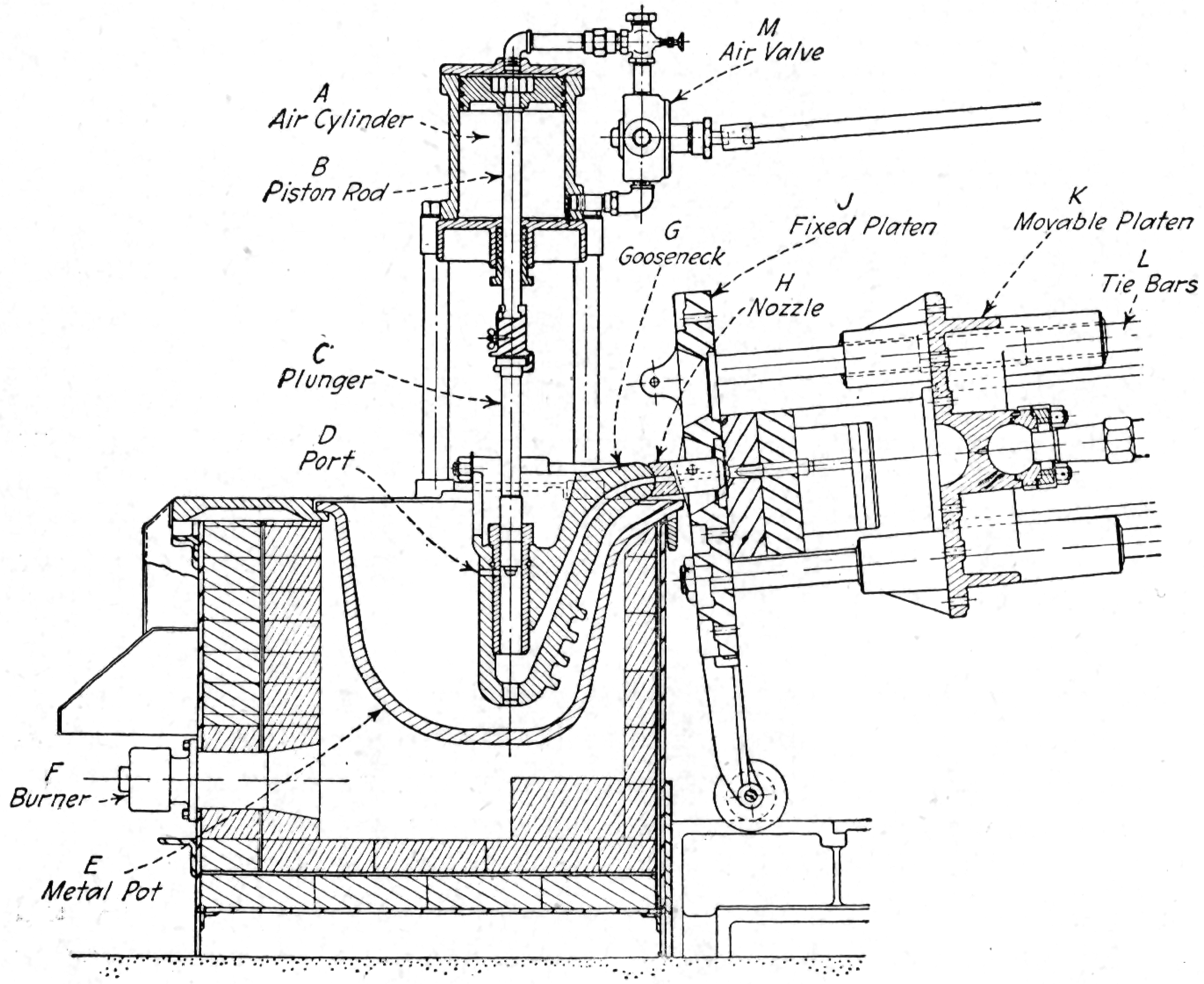

FIG. 5–7. Portion of modern die-casting machine for zinc alloy, showing vertical ram arranged for air operation.

5–19. Permanent Mold-Casting. Metallic or refractory molds capable of producing a large number of castings are known as permanent molds. Some permanent molds will produce thousands of castings. Like sand molds, permanent molds consist of two or more parts and are separated along some convenient parting line. They are also filled through a gate or gates without applied pressure except that exerted by the head of metal. The permanency of the mold depends on its ability to produce good castings with clean surfaces. Warpage caused by repeated heating and cooling as well as pitting which causes castings to stick shortens the useful life of the mold.

Permanent molds are made of cast-iron, steel, and bronze. The first two are used for both ferrous and nonferrous castings, while bronze is used for some of the low melting alloys. Prior to its use, the inner surfaces of the mold cavities are coated with refractory materials to avoid metal chill and to lessen the erosive effect of the molten metal. Hollow castings are made by means of either sand or metal cores, the latter being withdrawn from the metal before solidification is completed.

Permanent mold practice is adapted to the production of relatively small and simple castings and may be utilized for practically all casting alloys. It is more commonly applied to the casting of aluminum, magnesium, and copper alloys. Compared to sand-molding, the castings have a denser structure, closer dimensions, and are freer from gas pockets or blowholes. Castings which may become chilled or have a tendency toward cracking or tearing as they shrink should be removed from the mold while still hot, and cooled more slowly elsewhere.

5–20. Centrifugal-Casting. The production of long, hollow, cylindrical castings is accomplished by pouring molten metal through a trough into a rapidly rotating mold which revolves around a horizontal axis. Small castings of more or less symmetrical section are cast in vertically rotating molds. The speed of the rotation is governed by both the size of the casting and the characteristics of the metal, and it varies from about 600 to 3,000 rpm. By action of centrifugal force, the heavier metal is thrown against the inner surface of the mold while the lighter dross or slag, oxides, or inclusions are squeezed out and remain on the inner surface of the casting. The result is the formation of a thin or thick walled hollow cylinder of uniform thickness whose inner surface is circular in section.

Centrifugal molds are made of baked sand, carbon, or metal. Their inside surfaces may be either round, fluted, or polygonal. If any deviation from the normal cylindrical shape of the inner surface of the casting is required, refractory sand cores of the desired contour may be used. These, however, are used only infrequently, since in most instances the inside surface is advantageously machined to remove the impurities.

Centrifugal-casting is commonly employed for the production of cast-iron pipe, cylinder liners, Babbitt liners, gear blanks, large cast-steel gun barrels, and similar products.

Its most conspicuous advantages in comparison to sand-casting are (1) greater density; (2) finer grain structure; (3) relative freedom from gases and inclusions; (4) higher yield of casting per pound of metal poured (about equal to that obtained by the permanent mold practice); (5) higher tensile and yield strength and better surface on casting and therefore requiring less machining; (6) higher production rates; (7) more uniform distribution of alloying elements; and (8) better adaptability to the casting of long, hollow, cylindrical castings.

Its principal disadvantages are (1) that close tolerances are obtained only on the periphery of casting; (2) that molds rotating at the higher speeds should be dynamically balanced; (3) that it is not adaptable for some castings of intricate design—for example, long hollow castings with flanges or other protrusions; and (4) that size of castings is limited by effective rotating speeds.

QUESTIONS AND PROBLEMS

1. Design a simple part which may be made by either casting, forging, or welding. Compare as to cost, mechanical properties, and appearance.
2. Is casting necessarily an indispensable production process?
3. Discuss the advantages and disadvantages of raw sand and baked sand molding.
4. Draw a sand mold and designate drag, cope, cheek, core, gate, sprue, and parting line.
5. Make a list of binders used in core making.
6. What are core prints?
7. Discuss the relative merits of sand-casting, centrifugal-casting, and permanent mold-casting of copper-base alloy.
8. Discuss the advantages and disadvantages of the various die-casting alloys as to castability, cost, mechanical properties, stability, corrosion resistance, and weight.
9. Explain the use of match plates.
10. Compare the use of raw sand and baked sand molds for casting high shrinkage alloys.
11. Compare die-casting and permanent mold-casting.
12. What is the principal alloy in zinc-base die-castings?
13. Compare the various die-casting alloys as to relative corrosion resistance.
14. Give reasons why aluminum, magnesium, and copper alloys are die-cast in cold chamber machines.

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CHAPTER 6

FERROUS CASTINGS

Iron-base castings may be classified into three general groups, each of which consists of several subdivisions differing chiefly according to the percentage of the carbon, silicon, and/or alloying elements present. These divisions are shown in Table 6–1.

TABLE 6–1

CLASSIFICATION OF FERROUS CASTINGS

Cast-Iron	Malleable Cast-Iron	Castings
Gray	Standard	Low-C steel
Chilled	Cupola	Medium-C steel
White	White heart	High-C steel
Pearlitic	Pearlitic	Low-alloy
	Special	High-alloy

6–1. Gray Cast-Iron. Each year, approximately 10 to 15 million tons of industrial castings, known as gray cast-iron, are produced in the United States. These castings are produced in sand molds from mixtures of scrap cast-iron, steel, and pig iron melted in a furnace called a cupola, shown in Fig. 6–1. The average proportions in which these three are used for different applications are given in Table 6–2. Like the blast furnace, the cupola is a steel-encased, cylindrical structure that is heavily lined with firebrick, into which are charged in alternate layers, coke, iron, and a suitable flux, generally limestone. In contrast to the blast furnace, the cupola is relatively small. Its height from charging door to bottom varies from 8 to 30 ft with diameters from 24 to 82 in. Melting rates also show a wide variation, ranging from 2 to about 30 tons per hr. Its function, primarily, is to melt the metallic materials; it is not a refining process. It differs from the blast furnace in that (1) no ore is used; (2) charging is done through a side charging door; (3) it has no elaborate supplementary accessories such as hot stoves, cleaners, etc.; (4) no substantial change in the analysis of the metal occurs during its passage through; (5) the air blast is usually not preheated;* (6) it is of uniform diameter to the bottom of the stack; and (7) because of the comparative shallowness of the coke bed, the furnace atmosphere is oxidizing in contrast to the reducing function of the blast furnace.

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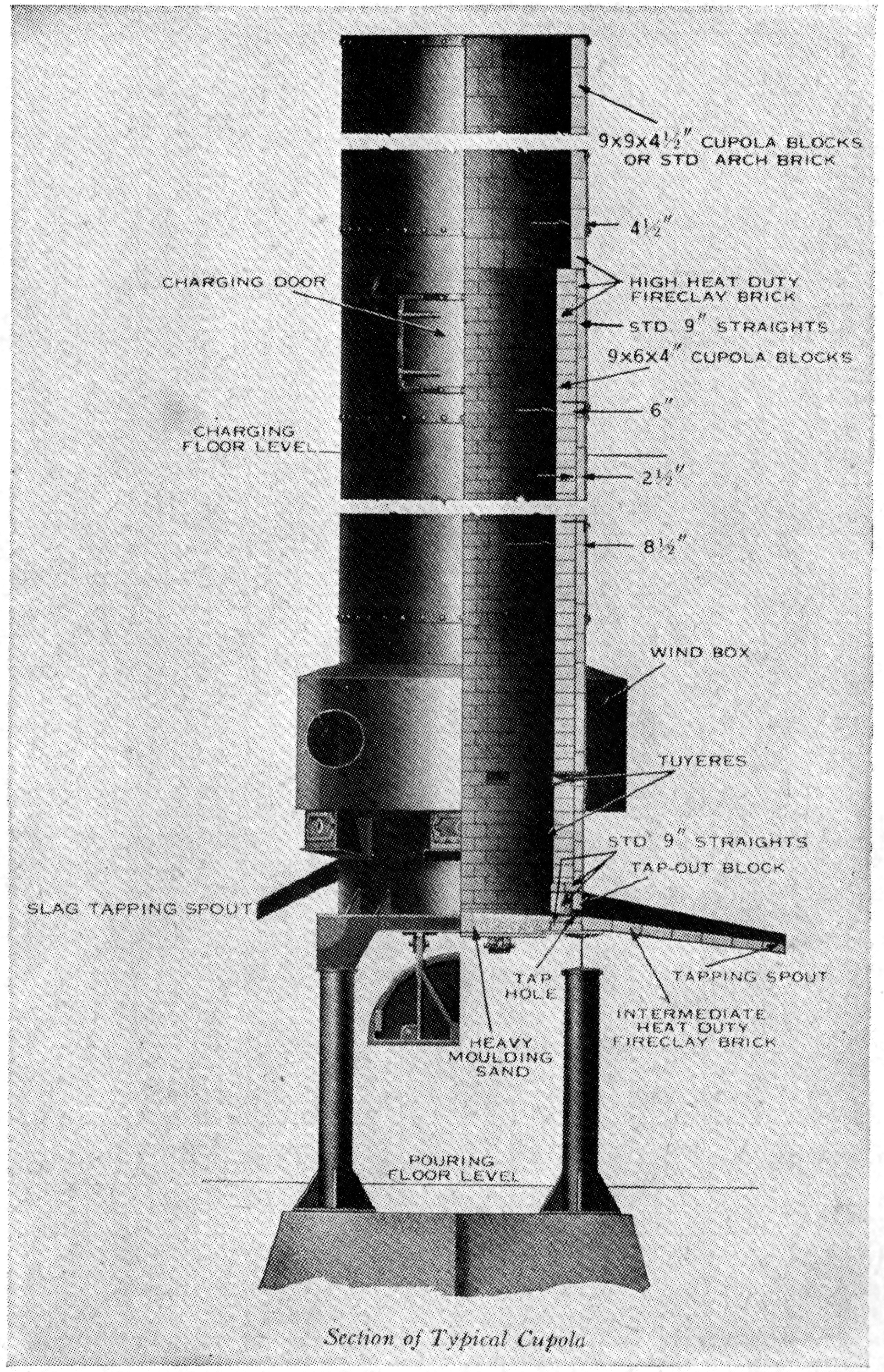
* Preheating the air increases the temperature, reduces silicon and manganese losses by 50 per cent, and produces all-round higher efficiency.

The proportion of the coke and iron charged, called a *burden*, differs widely between foundries. Most frequently, the ratio varies within the range of 1 part of coke to 8 or 12 of iron, by weight, plus about 3 parts of limestone as required to produce a slag of correct composition and fluidity. When sufficient metal has accumulated in the well, or the bottom, the furnace is tapped; and the molten metal flows through a spout into either large crane or *bull* ladles or smaller hand ladles, from which the metal is cast into the molds.


9x9x4½" CUPOLA BLOCKS OR STD ARCH BRICK
4½"
CHARGING DOOR
HIGH HEAT DUTY FIRECLAY BRICK
STD 9" STRAIGHTS
9x6x4" CUPOLA BLOCKS
6"
CHARGING FLOOR LEVEL
2½"
8½"
WIND BOX
TUYERES
STD 9" STRAIGHTS
TAP-OUT BLOCK
SLAG TAPPING SPOUT
TAP HOLE
TAPPING SPOUT
INTERMEDIATE HEAT DUTY FIRECLAY BRICK
HEAVY MOULDING SAND
POURING FLOOR LEVEL
Section of Typical Cupola

Courtesy of Harbison-Walker Co., Pittsburgh, Pa.

FIG. 6–1. Section of Cupola.

TABLE 6–2

TYPICAL ANALYSES OF SOME COMMERCIAL GRAY IRON CASTINGS*

CASTING	PER CENT							
	Total C	Si	Mn	P	S	Ni	Cr	Mo
Auto cylinder, plain iron	3.25	2.25	0.65	0.15	0.10	....	....	....
Auto cylinder, Ni–Cr iron	3.25	2.25	0.65	0.15	0.10	0.75	0.30	....
Auto cylinder, Ni–Cr iron, heavy duty	3.25	1.90	0.65	0.15	0.10	1.75	0.45	....
Auto cylinder, Ni iron	3.25	1.80	0.65	0.15	0.10	1.25	....	....
Auto pistons, plain iron	3.35	2.25	0.65	0.15	0.10	....	....	....
Auto pistons, Mo iron	3.35	2.25	0.65	0.15	0.10	....	....	0.50
General castings (auto), soft iron	3.40	2.60	0.65	0.30	0.10	....	....	....
Piston rings (auto), individually cast	3.50	2.90	0.65	0.50	0.06	....	....	....
Brake drums (auto)	3.30	1.90	0.65	0.15	0.08	1.25	0.50	....
Brake drums (auto)	2.75	2.25	0.70	0.15	0.08	....	....	0.50
Cams	3.10	1.50	0.65	0.15	0.10	2.00	0.60	....
Machinery iron:								
Light service or thin section	3.25	2.25	0.50	0.35	0.10	....	....	....
Medium service or heavy section	3.25	1.75	0.50	0.35	0.10	....	....	....
Heavy service with heavy section	3.25	1.25	0.50	0.35	0.10	....	....	....
Water pipe, sand-cast:								
Light and medium	3.60	1.75	0.50	0.80	1.08	....	....	....
Heavy	3.40	1.40	0.50	0.80	0.08	....	....	....
Chilled plow shares	3.60	1.25	0.55	0.40	0.10	....	....	....
High-strength iron, plain	2.75	2.25	0.80	0.10	0.09	....	....	....
High-strength iron, nickel	2.75	2.25	0.80	0.10	0.09	1.00	....	....
High-strength iron, Mo	2.75	2.25	0.80	0.10	0.09	....	....	0.35
Heat-resistant iron, fire pots, and kettles	3.50	1.15	0.80	0.10	0.07	....	....	....
Caustic pots, Ni–Cr	3.30	0.70	0.50	0.10	0.08	1.50	0.60	....
Caustic pots, plain	3.60	1.00	0.75	0.20	0.07	....	....	....
Ingot molds	3.50	1.00	0.90	0.20	0.07	....	....	....
Car wheels	3.35	0.65	0.60	0.35	0.12	....	....	....
Air cylinders, ammonia cylinders, plain iron	3.25	1.25	0.65	0.20	0.10	....	....	....
Heavy compressor cylinders, nickel iron	3.00	1.10	0.80	0.20	0.10	2.00	....	....
Light compressor cylinders, Ni–Cr	3.30	2.10	0.55	0.25	0.10	1.25	0.45	....
Light forming and stamping or forging dies, Ni–Cr iron	3.30	1.50	0.60	0.20	0.10	2.00	0.60	....
Heavy forming and stamping or forging dies, Ni–Cr iron	3.00	1.25	0.60	0.20	0.10	2.75	0.80	....
Light forging dies, Mo iron	3.30	2.00	0.60	0.20	0.10	....	....	1.00
Heavy forging dies, Mo iron	3.10	1.50	0.60	0.20	0.08	....	....	1.00
Valves and fittings (medium)	3.30	2.00	0.50	0.35	0.10	....	....	....

**ASM Handbook.*

Certain types of cast-irons are made from metals melted in electric furnaces or in air furnaces, either one of which permits much closer control over the analysis than is possible in the cupola. These processes are, however, more costly than cupola smelting. In some instances, the cupola is used in conjunction with an electric or other furnace, a practice known as *duplexing*, in which the metal is first melted in the cupola and then refined or superheated elsewhere.

6–2. Chemistry of Cupola Practice. The chemistry of gray iron founding, as ordinarily carried on, is relatively simple, since it involves no periodic analyses during the melting period and requires no control over the basicity or acidity of the slag, as in steelmaking. Metallurgically, only minor changes take place in the composition of the iron during its passage through the cupola. Unless precautions are taken to use only low-sulphur coke, this element will dissolve in the iron and show an increase, being present as FeS or MnS. Silicon and manganese are oxidized to silicon dioxide (SiO_2) and manganese oxide (MnO) by the oxide of iron and the excess oxygen of the blast, resulting in a loss of approximately 10 and 15 per cent of these elements, respectively. In general, the carbon varies according to (1) the total amount in the materials charged; (2) the carbon content of the fuel; (3) the pouring temperature; and (4) the melting rate—a high melting rate results in lower carbon absorption from the coke. Phosphorus remains practically unchanged so that the total amount in the castings is governed by the initial amount in the charge.

TABLE 6–3

Average Analysis of Plain Gray Cast-Iron in Per Cent

C	2.50–4.00
Si	0.50–3.00
Mn	1.00 max.
S	0.10–0.20
P	1.00 max.
Fe	remainder

Plain or unalloyed cast-iron is a ternary alloy of iron, carbon, and silicon and conforms to the analysis range given in Table 6–3.

6–3. Metallurgy of Gray Iron. While no sharp dividing line separates low-carbon cast-iron and steels containing from 0.83 to 1.70 per cent C, iron-carbon alloys with less than 1.70 per cent C are classified as steel, while those in which the carbon exceeds this value are classed as cast-irons. This differentiation is made on the basis of the solubility of solid carbide in gamma iron.

For a fuller understanding of this division, reference must be made to the iron–iron carbide equilibrium diagram shown in Fig. 9–6, where the changes in various phases during heating and cooling are shown.

From this, it is found that practically pure iron–iron carbide alloys containing over 1.70 per cent and less than 4.30 per cent C will, under equilibrium conditions of cooling, be composed at normal temperatures of pearlite and cementite or iron carbide, Fe_3C. Structurally, these alloys may be considered as high-carbon or hypereutectoid steels, since all the carbon is present as carbide. Alloys having this microstructure, shown in Fig. 6–2, are known as *white* iron castings, as discussed in the following material.

Provided, however, an alloy contains from 2 to 3 per cent silicon, the solubility of Fe_3C in austenite at the eutectic is reduced, and it is partly dissociated into its components—iron and carbon—during subsequent cooling. This reaction may be expressed: $Fe_3C + 3Si \rightarrow 3Fe\ Si + C$. With this decreased solubility of carbide, the carbon thus liberated is ejected and is present in the gamma iron as free graphite wholly uncombined with the iron. At the A_1 temperature (1333F), any remaining Fe_3C, which is soluble in the austenite that is stable at this temperature, transforms into pearlite by virtue of the simultaneous precipitation of both Fe and Fe_3C. Since silicon promotes graphite formation, gray iron castings may be produced under constant slow cooling, with the total carbon present partly as Fe_3C and partly as graphitic or free carbon. Therefore, when examined with a microscope, the structure of an appropriately polished and etched specimen of gray cast-iron is found to consist of three constituents—ferrite, pearlite, and graphite. As shown in Table 6–4, alloying elements commonly added influence the carbide dissociation. Solubility is affected also by cooling rate; the degree of graphitiza-

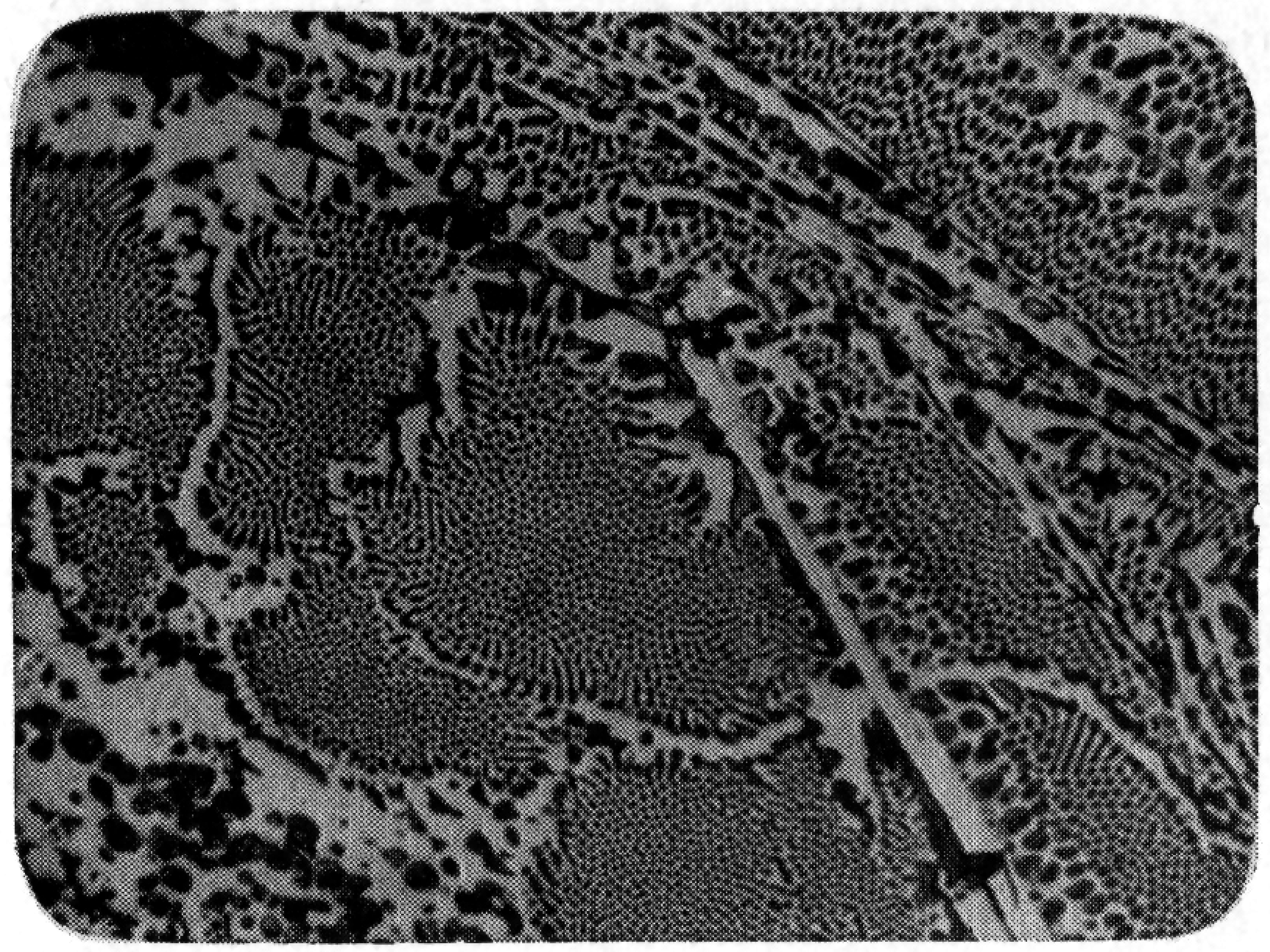


Fig. 6–2. Hypereutectic white cast-iron, showing primary cementite and ledeburite eutectic. C about 4.5 per cent. ×100. (Courtesy of School of Mines and Metallurgy, University of Minnesota.)

tion, as well as the size of the agglomerated flakes, vary inversely as the rate of cooling. It is possible, therefore, with the proper adjustment of the chemical composition and a controlled cooling rate of the castings in the mold to obtain these three constituents in almost any desired proportions and thus produce irons whose fracture will be gray (graphitic), mottled (pearlitic), or silvery white (white iron) in color. In this manner the mechanical properties of cast-irons are most effectively and economically modified or controlled. A photomicrograph of gray cast-iron is shown in Fig. 6–3.

TABLE 6–4

SUMMARY OF STRUCTURAL EFFECTS OF ALLOYS ON CAST-IRON*

Elements	Percentages Used in Pearlitic Irons (Per Cent)	Effect on Carbides (at High Temperatures)	Effect on Graphite Structure	Effect on Combined Carbon in Pearlite	Effect on Matrix
Chromium....	0.15–1.0	Strongly stabilizes	Mildly refines	Increases	Refines pearlite and hardens
Vanadium....	0.15–0.50	Strongly stabilizes	Refines	Increases	Refines pearlite and hardens
Manganese...	0.30–1.25	Stabilizes	Mildly refines	Increases	Refines pearlite and hardens
Molybdenum..	0.30–1.00	About neutral	Strongly refines	Mildly increases	Refines pearlite and strengthens
Copper......	0.50–2.0	About neutral	About neutral	Mildly decreases	Hardens
Carbon......	....	Decreases stability	Coarsens	Strongly decreases	Produces ferrite and softens
Silicon......	....	Decreases stability	Coarsens	Strongly decreases	Produces ferrite and softens
Aluminum....	....	Decreases stability	Coarsens	Strongly decreases	Produces ferrite and softens
Nickel.......	0.10–3.0	Mildly decreases	Mildly refines	Mildly decreases	Refines pearlite and hardens
Titanium.....	0.05–0.10	Decreases stability	Strongly refines	Decreases	Produces ferrite and softens
Zirconium....	0.10–0.30	....	About neutral	....	Produces ferrite and softens

* Merica, P. D., *Transactions, AIME*, Vol. 125 (1937).

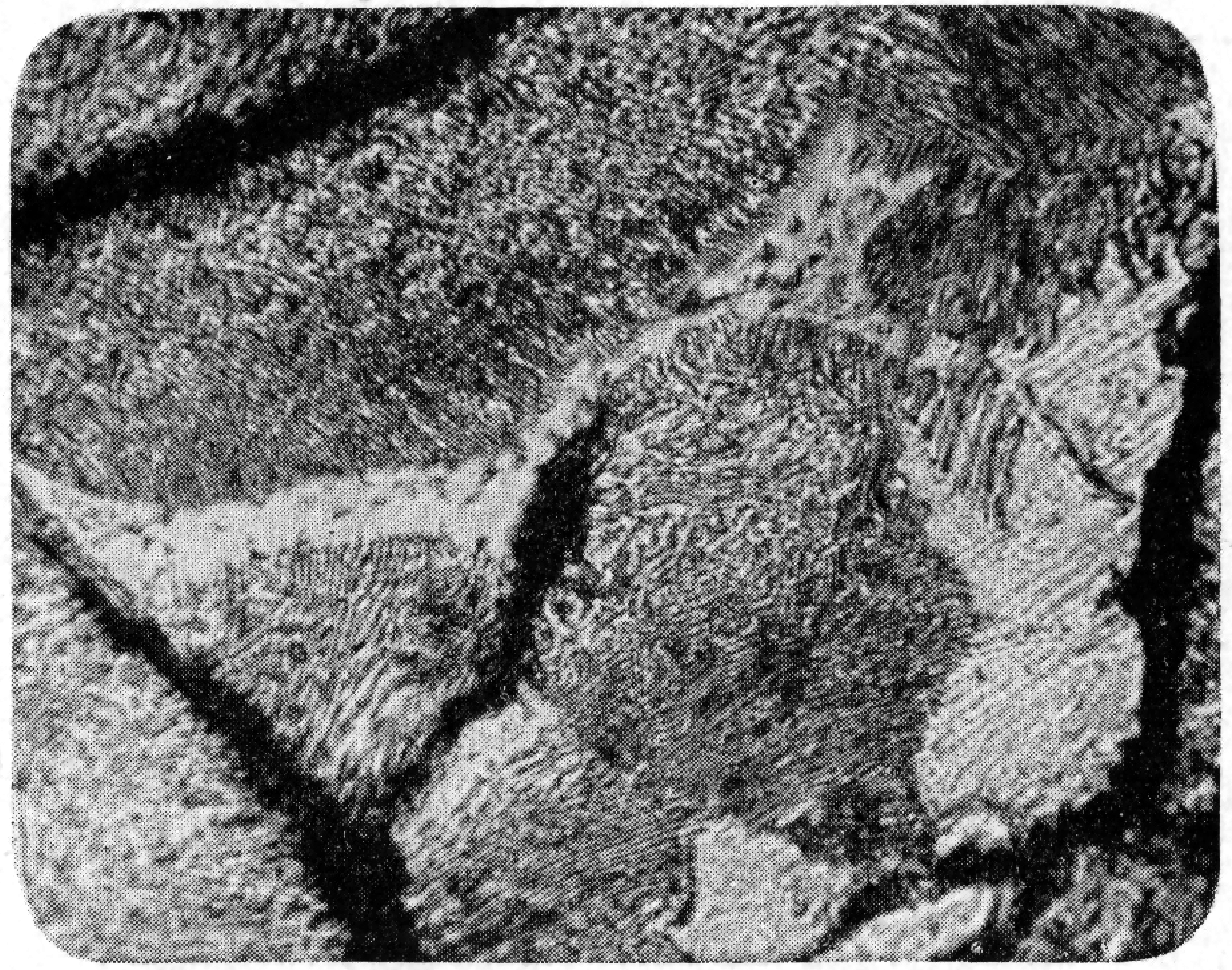


FIG. 6–3. Photomicrograph of plain gray cast-iron. White areas are ferrite; dark areas are pearlite; black areas are graphite. ×1000. (Courtesy of Dr. R. L. Dowdell, School of Mines, University of Minnesota.)

The total of combined carbon in gray cast-irons is usually less than that in eutectoid steel, although in the higher strength or pearlitic irons it approaches this value. The effects of varying proportions of graphite and Fe_3C on mechanical properties becomes obvious from a comparison of the characteristics of graphite and carbide, the former being weak and soft and the latter hard, strong, and brittle. Hence, the static strength of cast-iron varies in direct proportion to the amount of combined carbon, while the machinability varies inversely.

For some applications, castings are *chilled* by inserting metallic heat conductors in the molds to accelerate the cooling by heat transfer; and thus the castings retain carbon in the combined form in that area, while other parts cool normally to produce gray iron. For example, railroad car wheels, which are chilled on the tread to increase wear resistance, are produced at an annual rate of over 2,000,000 wheels. Parts of equipment for crushing grains, ores, coal, and cement materials, and rolls for rough and finish rolling of metals are other examples of the use of chilled products.

6–4. Mechanical Properties of Gray Cast-Iron. The outstanding characteristics of gray cast-iron are (1) low initial cost; (2) good machinability (this property varies inversely as the strength and hardness);

(3) excellent capacity for effectively absorbing or *damping* vibrations or oscillations; (4) low impact value; (5) good frictional wear resistance; (6) insensitivity to a notch or surface irregularity; (7) high relative compressive breaking strength. The high damping quality and the high compressive-tensile strength ratio* are attributable to the presence of the graphite flakes, which cause a discontinuance of the metallic matrix and permit plastic deformation of the metal surrounding these at lower nominal stresses than would otherwise be the case.

TABLE 6–5

CLASSIFICATION OF CAST-IRON*

CLASS NO.	TENSILE STRENGTH (Minimum Psi)	MINIMUM TRANSVERSE STRENGTH IN POUNDS		
		12-In. Support	18-In. Support	24-In. Support
20	20,000	900	1,800	6,000
25	25,000	1,025	2,000	6,800
30	30,000	1,150	2,200	7,600
35	35,000	1,275	2,400	8,300
40	40,000	1,400	2,600	9,100
50	50,000	1,670	3,000	10,300
60	60,000	1,925	3,400	......

* ASTM Specifications A-48-41.

The mechanical properties of gray cast-iron are determined mainly by tensile and transverse test, as described in Chapter 3. The various irons classified on this basis with minimum requirements are shown by Table 6–5. The average typical properties of these grades of gray iron are given in Table 6–6.

The effect of section size or mass of cast bar on the Brinell hardness and the tensile strength of representative castings is shown in Table 6–7 and Table 6–8.

6–5. Pearlitic or High-Strength Cast-Irons. High-strength cast-irons include a wide range of compositions of both the alloyed and unalloyed types. The improved mechanical properties of the unalloyed type result from (1) increasing the relative proportion of steel scrap over pig iron and cast-iron in the cupola or furnace charge, thus lowering the total carbon and silicon; (2) melting in the absence of coke such as in an electric or air furnace; or (3) processing low-silicon iron in the ladle with various constituents known as *inoculants*, to obtain a finer distribution of the graphite and to increase the pearlitic matrix. In addition to the factors listed above irons of higher strength result if the cooling rate is accelerated by the use of chills or by reducing the size of sections.

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* The compressive-tensile strength relation varies from 4.5 to 1 for low-strength iron to 2.5 to 1 for high-tensile iron.

TABLE 6–6

AVERAGE TYPICAL PHYSICAL PROPERTIES OF VARIOUS GRADES OF GRAY CAST-IRON*

Physical Properties	Class 20	Class 25	Class 30	Class 35	Class 40	Class 50	Class 60
Tensile strength, psi	22,500	27,500	32,500	37,500	45,000	55,000	65,000
Transverse strength, load-lb	2,000	2,100	2,200	2,600	2,900	3,300	3,700
Deflection, in.	0.25	0.27	0.28	0.28	0.28	0.28	0.34
Modulus of rupture, psi	53,000	55,700	58,400	69,000	78,000	87,600	98,000
Compressive strength, psi	95,000	100,000	115,000	125,000	143,000	150,000	170,000
Shear strength, psi	32,000†	37,000†	44,000†	43,000†	57,000†	59,000	
Impact strength, ft lb	55‡	55‡	61‡	60‡	80‡	115‖	
Endurance limit, psi	10,000	12,500	14,500	17,500	21,000	25,000	
Brinell hardness	180	190	200	210	220	240	290
Modulus of elasticity, millions psi	12§	13§	15§	16§	17§	19§	19½§
Transverse resilience in lb	350	400	430	450	600	700	800
Total carbon	3.01–3.58	2.85–3.54	3.12–3.53	3.10–3.62	2.50–3.25	2.76–2.95	2.55–3.05
Graphite carbon	2.82–2.96	2.64–2.90	2.44–2.72	2.30–2.66	1.50–2.52	1.82–2.12	1.92–2.08
Combined carbon	0.57–0.64	0.64–1.07	0.58–0.71	0.64–0.87	0.70–1.00	0.83–1.04	0.63–0.92
Silicon	1.56–2.93	1.21–2.35	1.14–2.46	0.68–2.69	1.15–2.22	1.49–2.44	1.68–2.70
Manganese	0.42–0.69	0.32–0.73	0.44–0.90	0.58–0.82	0.59–0.94	0.41–1.13	0.50–1.00
Phosphorus	0.14–1.20	0.14–0.90	0.16–0.63	0.14–0.54	0.04–0.43	0.03–0.21	0.04–0.15
Sulphur	0.05–0.12	0.06–0.08	0.07–0.12	0.06–0.10	0.06–0.10	0.045–0.117	0.032–0.12

* Test bars 1.2 in. as-cast.
† Shear on 0.505 in. diameter specimens.
‡ Charpy test 1.20-in. diameter. Bar 18 in. support.
§ Modulus at ¼ transverse load.
‖ Impact specimens machined and ground to 1.25 in. diameter. Broken on 6-in. centers.

The various alloying elements added to a gray iron charge have a distinctive influence on the structure and result in still higher values for such mechanical properties as tensile strength, transverse strength and deflection, as well as in increased resistance to heat, wear, and corrosion. Plain gray iron is unsuitable for service encountered in various engineering undertakings in which these conditions predominate; and, therefore, various alloying elements are added. By stabilizing the carbide, these elements refine the basic structure and influence the size, shape, and dispersion of the graphite particles, and thus yield an iron possessing higher mechanical properties than an unalloyed iron of similar carbon content. The alloy elements added are of two kinds: those strongly inhibiting a tendency to graphitize; and those, when added in sufficient quantities, producing irons almost wholly graphitic or ferritic. Control over this phase of cast-iron metallurgy is one of the most important factors in obtaining consistent and satisfactory properties.

TABLE 6–7

INFLUENCE OF SIZE OF CAST-IRON SECTION ON BRINELL HARDNESS

IRON	COMPOSITION					BRINELL HARDNESS Test Bar Diameters (In.)			
	C	Si	Mn	S	P	3.0	2.0	1.2	0.875
A	3.30	2.21	0.59	0.08	0.54	179	207	217	228
B	3.47	2.15	0.48	0.08	0.66	143	187	228	248
C	3.25	2.42	0.57	0.08	0.48	153	207	228	255
D	3.31	2.14	0.74	0.09	0.74	179	212	235	248
E	3.42	2.39	0.59	0.08	0.58	137	187	235	241

TABLE 6–8

TENSILE STRENGTH (PSI) IN BARS AS-CAST AND MACHINED

IRON	DIAMETER OF BARS AS-CAST			
	3 In.	2 In.	1.2 In.	0.75 In.
	DIAMETER OF MACHINED BAR			
	0.80 In.	0.80 In.	0.80 In.	0.505 In.
A	18,600	24,150	35,210	36,475
B	14,380	18,080	25,430	27,200
C	22,700	27,450	35,960	37,500
D	24,540	30,900	36,870	37,375
E	12,100	15,420	23,590	28,825

The alloying elements most commonly found in gray cast-iron are nickel, chromium, molybdenum, vanadium, and copper. Aluminum and zirconium, added to special grades of iron in the ladle just prior to pouring, function as graphitizers and particularly as deoxidizers. The alloys are added singly or, more frequently, in combinations such as nickel-chromium, etc. The proportions in which they are used and their specific influences are given in Table 6–3.

6–6. Influence of Constituents on Gray Cast-Iron. *Manganese.* In the amounts of 0.40 to 1.00 per cent, such as are usually found in cast-iron, the principal function of manganese is to form with sulphur the harmless compound MnS, thus reducing the tendency of sulphur to oppose the graphitizing influence of silicon. When present in larger amounts (over 1.25 per cent), manganese increases the strength, resistance to wear, hardness, and depth of chill, and decreases the machinability. In low-carbon low-silicon alloys, manganese progressively produces a matrix consisting of pearlite, sorbite, martensite, and, with over 10 per cent manganese, austenite.

Sulphur. Provided sufficient Mn is present, sulphur in the amount of 0.10 to 0.15 per cent as found in cast-irons is not harmful. Unless thus neutralized by Mn, sulphur causes hard spots and opposes the silicon reaction.

Phosphorus. Phosphorus is present in cast-irons in amounts from 0.15 to 0.90 per cent. Its principal role is that of increasing flowability of the metal, thus facilitating the production of thin walled castings.

While small amounts (under 0.30 per cent) of P do not materially affect the properties, higher amounts tend to reduce the tensile and transverse strengths. With higher percentages, a hard, brittle, structural component of a low melting point, called steadite (Fe_3P), is formed.

6–7. Malleable Cast-Iron. As pointed out before, the cooling of low-silicon high-carbon alloys results in a microstructure consisting wholly of pearlite and cementite. These practically unmachinable and extremely brittle white irons have but a very limited industrial application. Because of their extreme hardness, however, they possess excellent resistance to abrasive wear. Their production is the first phase in making malleable cast-irons, as described in the following material.

The usual furnace charge for malleable iron production consists of pig iron, malleable and steel scrap, sprues, and gates. These are selected (making due allowance for some loss of silicon, manganese, and carbon and for an increase in the sulphur content) so as to contain those amounts of silicon, manganese, carbon, phosphorus, and sulphur that are desired in the final composition.

A typical charge for the manufacture of standard malleable iron is given in Table 6–9.

While some low-strength malleable cast-iron for use as pipe fittings is melted in the cupola, standard malleable castings are produced of

TABLE 6–9*

Average Furnace Charge for Standard Malleable Iron

	Air Furnace (Per Cent)	Duplexing (Per Cent)
Pig iron	32	18
Sprue and gates	50	50
Malleable scrap	14	10
Steel scrap	4	22

* *Handbook*, American Malleable Iron Association.

metal melted in a reverberatory air furnace, shown in Fig. 6–4, in which pulverized coal or oil is generally used as fuel.

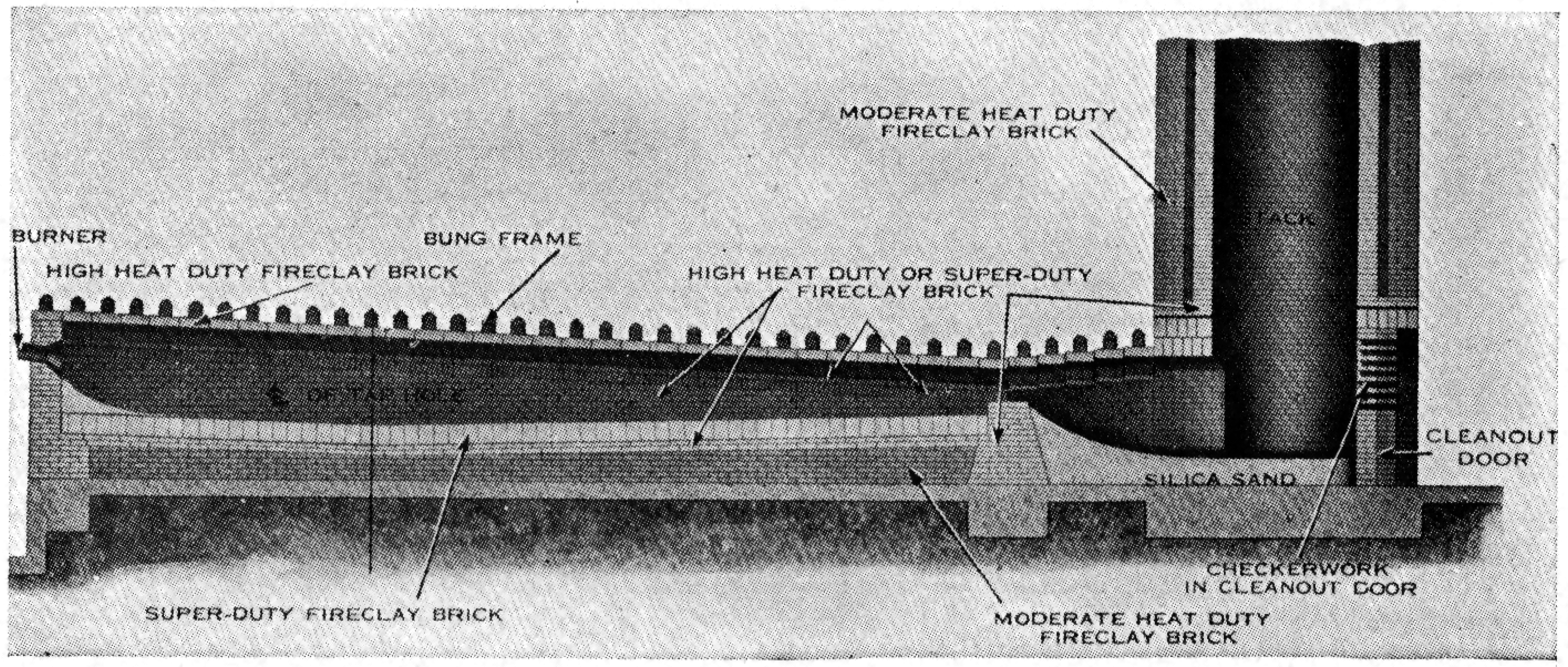
MODERATE HEAT DUTY FIRECLAY BRICK
STACK
BURNER
BUNG FRAME
HIGH HEAT DUTY FIRECLAY BRICK
HIGH HEAT DUTY OR SUPER-DUTY FIRECLAY BRICK
℄ OF TAP HOLE
CLEANOUT DOOR
SILICA SAND
CHECKERWORK IN CLEANOUT DOOR
SUPER-DUTY FIRECLAY BRICK
MODERATE HEAT DUTY FIRECLAY BRICK

Fig. 6–4. Sectional view of a reverberatory melting furnace. (Courtesy of Harbison-Walker Co., Pittsburgh, Pa.)

In a process known as duplexing, the iron is first melted in a cupola, then transferred to the air furnace for refinement and additional heating. Less frequently, the electric and open-hearth furnace processes are also used.

An air furnace consists of a shallow hearth with an arched roof which directs the combustion gases onto the hearth. In addition to the time required to melt the metals, additional time is required to oxidize some of the silicon to SiO_2 and the carbon to CO or CO_2 and thus insure that the metal structure as-cast shall consist wholly of cementite and pearlite. A total time of 4 to 6 hr is necessary to melt a furnace charge of 20 to 25 tons. The iron is tapped from a spout in the lowest part of the hearth and, like gray iron, is cast into molds at a temperature of about 2700 to 2800F.

Following the solidification of the metal in the mold, the castings are shaken out and the gates and sprues broken off. After being cleaned by sandblasting or *tumbling* in a barrel, they are heated to malleablize or anneal, a heat treatment which constitutes a most essential metallurgical phase of the production of the malleable cast-iron.

Remembering the properties of white iron and the physical characteristics of iron carbide predominating in its structure, it is obvious that a metallurgical transformation of this constituent must take place before any semblance of malleability can be attained. It is, therefore, for the purpose of dissociating the carbide into ferrite and carbon and controlling the distribution or agglomeration of the latter that the heat treatment of these castings is undertaken.

The American method of producing *black heart* malleable iron involves packing the white iron castings in iron boxes with pulverized furnace slags, sand, cinder or iron oxide, or mill scale (Fe_3O_4) to support the castings and help prevent their distortion during the heating and the time they are held at temperature. The boxes luted with clay are stacked on one another and heated to the proper temperature, held, and cooled at a rate consistent with the size, degree of dissociation, and properties required in the castings. The normal cycle consists of heating from 1500 to 1650F as quickly as practically feasible to obtain uniformity, holding at this temperature for 50 to 60 hr and cooling 8 or 10 degrees per hour until the castings have reached 1300 to 1250F, and then cooling more rapidly for a period of 60 hr. Depending on the type of furnace used, the total annealing cycle varies from 3 to 6 days.

Accurate temperature control and adequate furnace facilities have enabled manufacturers to dispense with the boxes and to shorten the heat-treating cycle to less than ⅓ the time of the usual practice. The malleablizing treatment may be carried out to the partial or even complete elimination of the carbide. When only partially malleablized, the castings have a pearlitic matrix. If a complete graphitization is not desired, small amounts of retarders or inhibitors such as manganese, chromium, or molybdenum are used. The existence of a pearlite matrix decreases both the ductility and machinability of the castings but increases their ultimate tensile strength in proportion to the amount and distribution of the pearlitic aggregates. When fully malleablized, the iron should possess a structure consisting wholly of ferrite, with graphite in round nodules or *rosettes* of temper carbon in contrast to the flakes present in gray iron. Compare Fig. 6–5 and Fig. 6–3. Any semblance to a flaky graphitic structure is evidence of (1) an incorrect carbon-silicon ratio; (2) too slow a cooling rate of the original casting in the mold; and (3) too high an annealing temperature. Since the continuity of the ferrite base or matrix is less affected than in gray iron, malleable cast-irons possess superior physical properties, as pointed out in Table 6–10. They also possess better machinability than any other ferrous product of comparable properties.

The metallurgy of the malleablizing process involves the solution of the carbide in the austenite and its subsequent precipitation as graphite particles, according to the equation: $Fe_3C + \text{heat} \rightarrow 3Fe + C$ (graphite). The free graphite of malleable castings is chemically identical to that in gray iron differing only in its form.

The addition of alloying elements to malleable cast-iron does not at present seem to be feasible, and only copper and molybdenum have been used to any appreciable extent.

In contrast to the American practice of producing black heart malleable iron, in Europe the castings are heated in contact with iron oxide to *decarburize,* or remove the carbon from the surface or skin of the castings, thus producing a degree of malleability in this region without effecting any substantial change in the core or interior, which remains largely as white iron. Hence, the name *white heart* malleable. These castings are characterized by a lower ductility and a higher tensile strength than are found in the American product.

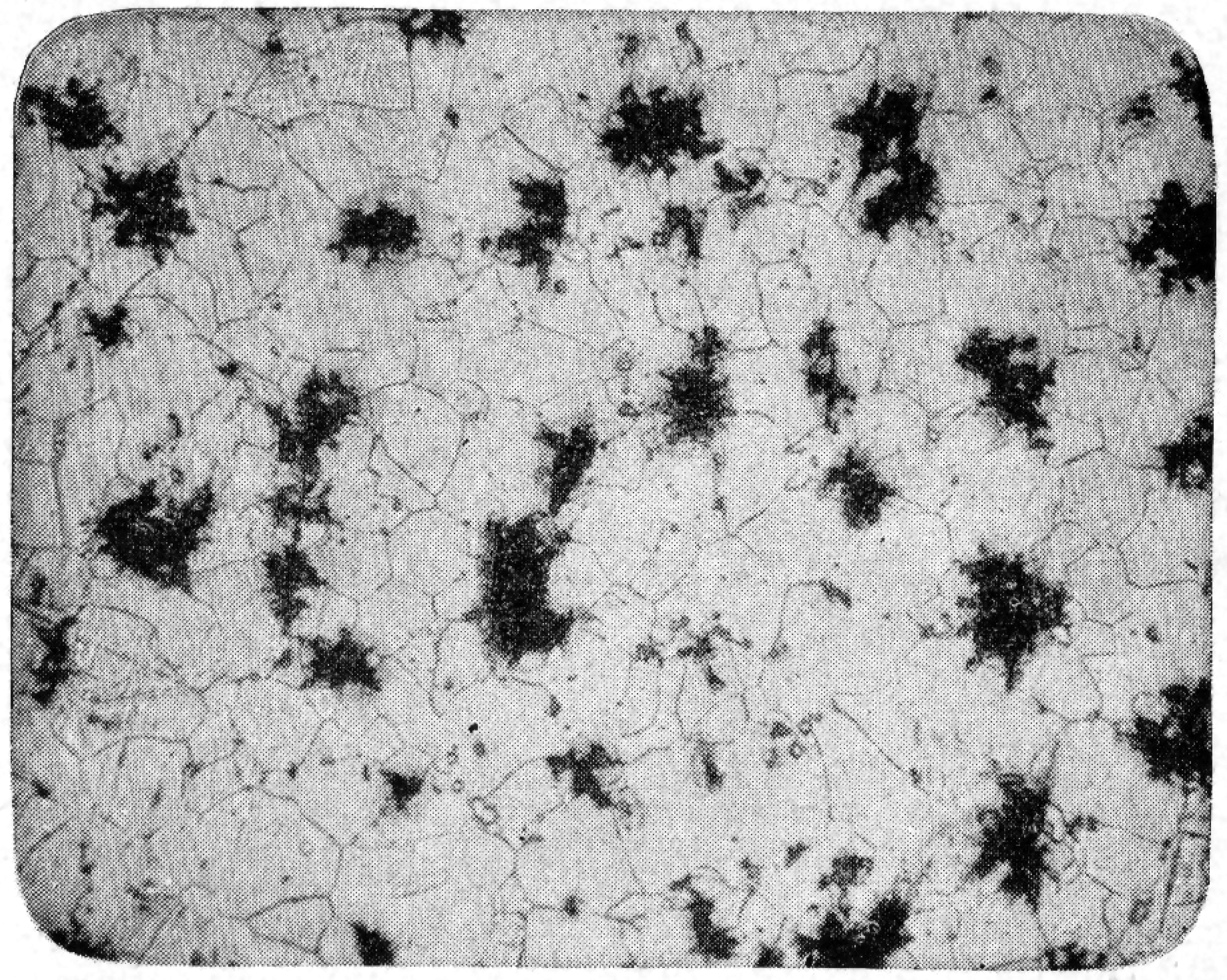

FIG. 6–5. Photomicrograph of typical black heart malleable cast-iron. White matrix consists of ferrite with nodules of graphite. ×100. (Courtesy of Dr. R. L. Dowdell, School of Mines, University of Minnesota.)

6–8. Applications and Uses of Malleable Cast-Iron. Malleable cast-iron is not recommended for use where temperatures attained exceed the A_1 critical or 1333F. Above this temperature, the carbon redissolves in the austenite and, unless subsequent cooling rates are comparable to those of the original malleablizing process to allow for its reprecipitation as graphite, the resultant structure will consist of metastable products like those of heat-treated steels. This condition reduces ductility in direct

TABLE 6–10

SUMMARY OF DATA ON THE COMPOSITION AND PROPERTIES OF MALLEABLE IRON

COMPOSITION AND PROPERTIES	ASTM SPECIFICATION A47-33, GRADE 35018		ASTM SPECIFICATION A47-33, GRADE 32510	
	Range	Most Probable Value	Range	Most Probable Value
Chemical composition—white iron:				
Carbon, per cent	1.75–2.30	......	2.25–2.70	......
Silicon, per cent	0.85–1.20	......	0.80–1.10	......
Manganese, per cent	Less than 0.40	......	Less than 0.40	......
Phosphorus, per cent	Less than 0.20	......	Less than 0.20	......
Sulphur, per cent	Less than 0.12	......	0.07–0.15	......
Chemical composition—finished product:				
Temper carbon, per cent	Less than 1.80	......	Less than 2.20	......
Silicon, per cent	Less than 1.20	......	Less than 1.10	......
Manganese, per cent	Less than 0.40	......	Less than 0.40	......
Phosphorus, per cent	Less than 0.20	......	Less than 0.20	......
Sulphur, per cent	Less than 0.12	......	Less than 0.13	......
Physical properties:				
Specific gravity	7.20–7.45	......	7.34–7.25	......
Shrinkage allowance, in. per ft	1/8–3/16 in.	3/16 in.	1/8–3/16 in.	3/16 in.
Coefficient of thermal expansion				
per degree C	......	0.000012	......	0.000012
per degree F	......	0.0000066	......	0.0000066
Specific heat varies with temp.; average value between 20 and 100 C	......	0.122	......	0.122
Mechanical properties:				
Tensile strength, psi	53,000–60,000	57,000	50,000–52,000	50,000
Yield point in tension, psi	35,000–40,000	37,500	32,500–35,000	32,500
Elongation in 2 in., per cent	18–25	22	10–18	14
Reduction of area, per cent	18–23 per cent	20	18–23 per cent	20 per cent
Modulus of elasticity in tension, psi	......	25,000,000	......	25,000,000
Poissons ratio	......	0.17	......	0.17
Ultimate shearing strength, psi	......	48,000	......	48,000
Yield point in shear, psi	......	23,000	......	23,000
Modulus of elasticity in shear, psi	......	12,500,000	......	12,500,000
Modulus of rupture in torsion, psi	......	58,000	......	58,000
Brinell hardness number	......	110–145	110–135	......
Charpy impact value, ft-lb (using V notch 0.394 in. square bar, 0.79 in. depth of notch)	......	16.5	......	......
V notch 0.197-in. deep	......	7.0	......	6.5
Izod impact value, ft-lb (using V notch 0.394 in. square bar, 0.079 in. depth of notch)	......	16.5	......	......
Fatigue endurance limit, psi	......	25,000–26,500	25,000–26,500	25,500
Endurance ratio, endurance limit/ultimate strength	0.43–0.54	0.50	......	0.50
Resistivity, micro-ohms per cube	......	28.84–34.36	......	32.07

proportion to the cooling rate. For these reasons malleable cast-iron is not usually fusion-welded to effect repairs; but, if the casting is correctly preheated, welded with a white iron welding rod, and re-annealed, fusion-welding by the oxyacetylene method may be satisfactory. The usual procedure, however, is to bronze-weld it like gray cast-iron employing the lowest temperature at which the bonding can be effected and retaining for the shortest time.

Unless heated beyond the critical temperature, malleable cast-iron shows no tendency to dimensional growth, such as is shown by gray cast-iron, and its tensile strength remains unimpaired up to about 800F.

Because of its strength, ductility, machinability, and resistance to shock, malleable cast-iron is used for a wide diversity of industrial applications, including agricultural implements, hardware for windows, doors, etc., conveyor and elevator equipment, automobiles and trucks, railroad and marine equipment, and other machinery parts.

6–9. Steel Castings. During a normal production period, approximately 1,000,000 tons of steel castings are produced each year in the United States. Of this amount, approximately 20 per cent is classed as alloys. In common with other castings, steel castings comprise a large variety of shapes and degrees of complexity. They range in weight from a few ounces to over 230 tons.

The largest proportion of this total tonnage is the product of the acid and basic open-hearth and acid electric furnaces. A few foundries, however, employ small side-blown converters called "Tropenas" of 1- or 2-ton capacity for the refining of molten cupola iron. Except that the air enters *through* the trunnions and plays over the *surface* of the metal, instead of through a wind box underneath, these converters are similar to the Bessemer. The induction furnace is also used for producing castings of high-alloy content. Foundry furnaces are smaller, but their operation and the metallurgy of the processes are similar to those in steel mills. The capacity of foundry open-hearths varies from 5 to 50 tons and that of the electric from 2 to 25 tons.

Procedures in molding and the use of patterns also are similar to those followed in making other castings. Because of the lower carbon content, however, the melting point of the metal is higher, with consequent higher pouring temperatures, than that of either gray or malleable iron. This necessitates the use of a more refractory molding sand. For this purpose either a high-grade natural silica sand or a synthetically bonded sand, washed and graded to a uniform size, is utilized.

Before becoming completely cold, large castings of complex shape are often removed from the mold and placed in a furnace where their cooling is controlled as a precaution against possible shrinkage cracks or tears, caused by high internal stresses incident to too rapid or uneven cooling.

A furnace charge consists of scrap steel, sprues, and risers from previous *heats*, and pig iron of an analysis consistent with the type of castings and physical properties desired. When required, alloying elements are added by weight either to the charge in the furnace or in the ladle, according to the oxidizing characteristics of the alloying elements and the melting process used.

The analysis of plain carbon steel castings is similar to that of wrought steels, except that castings usually contain a higher percentage of manganese and silicon in proportion to the carbon. These two elements function as deoxidizers by removing the gases soluble in molten metal as solids before the metal solidifies (when the solubility decreases); they thus minimize defects commonly known as *blowholes*.

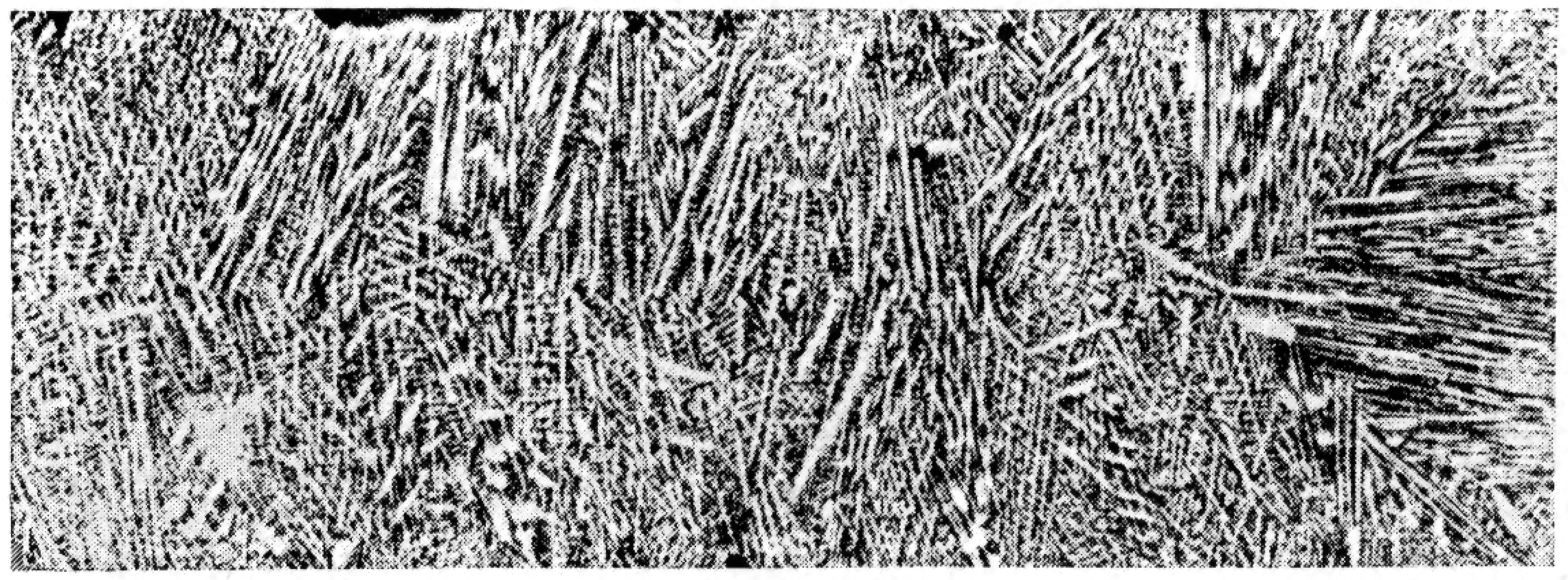

FIG. 6–6. Macrograph of low-carbon steel casting, showing dendritic structure. ×1. (Courtesy of Dr. R. L. Dowdell, School of Mines, University of Minnesota.)

The microconstituents of cast and wrought steels are also similar: ferrite and pearlite. As discussed in Chapter 7, the normally slow cooling of steel results in the formation of a dentritic, coarse-grained structure. In hypoeutectoid steels, precipitation of ferrite along crystallographic planes creates an angular, needlelike pattern known as *Widmanstatten* structure. This is shown in Fig. 6–6. In hypereutectoid steels this takes the form of a carbide grain boundary network.

Since no graphite is present, carbon and low-alloy steel castings are malleable in all temperature ranges and, therefore, may be hot-worked, flame-cut, and welded, either to themselves or to other weldable steels.

6–10. Classification of Unalloyed Steel Castings. Unalloyed steel castings are generally divided into three groups, as shown in Table 6–11, and are known as low-, medium-, and high-carbon. The low- and high-carbon castings are termed special, while the medium-carbons are termed the regular grade. These constitute the greatest proportion of steel castings.

6–11. Heat Treatment of Steel Castings. As will be pointed out in Chapter 11, the mechanical properties of all metals in the as-cast condition

TABLE 6–11

CLASSIFICATION AND ANALYSES OF CARBON STEEL CASTINGS

Type	Analyses (Per Cent)				
	Carbon	Manganese	Silicon	Phosphorus	Sulphur
Low-carbon........	0.11–0.18	0.50–0.85	0.25–0.70	0.05 max.	0.06 max.
Medium-carbon....	0.20–0.50	0.50–1.00	0.20–0.70	0.05 max.	0.06 max.
High-carbon.......	0.50–1.00	0.50–1.00	0.20–0.70	0.05 max.	0.05 max.

are inferior to those of the same metals in the heat-treated or mechanically worked state. With the possible exception of those in the lowest carbon range, and where service requirements do not demand higher properties, steel castings are generally subjected to some form of heat treatment, with a view to improving their properties, before they are placed in service. The principal methods used are normalizing, annealing, and quenching in either oil or water, followed by a reheating to *draw* or *temper*. The structural effects of these operations may be seen by comparing the photomicrographs shown in Figs. 6–7, 8, 9, 10, and 11. The compositions and mechanical properties of carbon and alloy steel castings are given in Table 6–12. The wide range in properties is attributable to the influence of heat treatment.

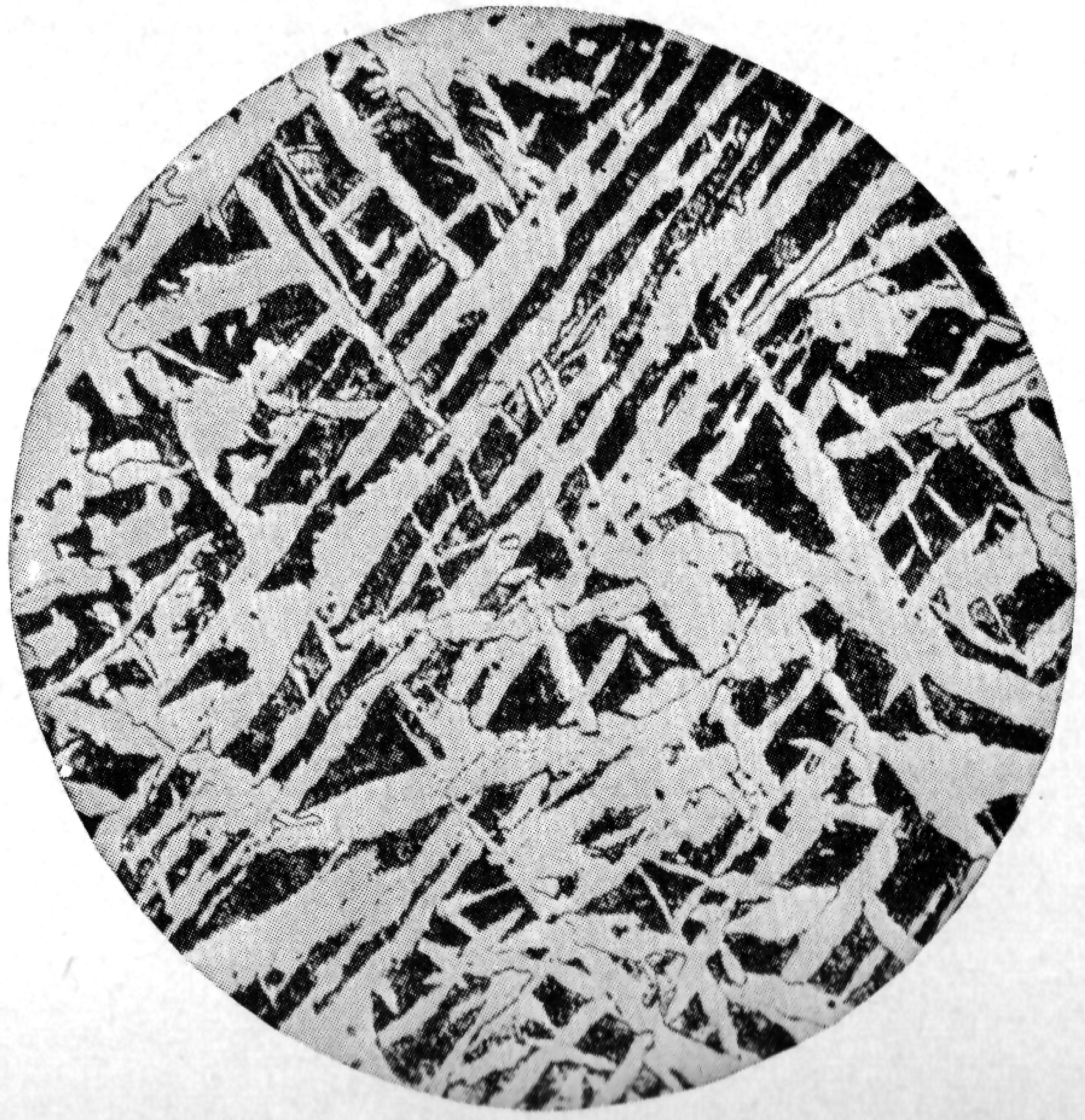

FIG. 6–7. Medium carbon steel in "as-cast" condition. ×25. (Courtesy of Mr. Herbert Blosjo, metallurgist, Minneapolis Electric Steel Castings, Minneapolis, Minn.)

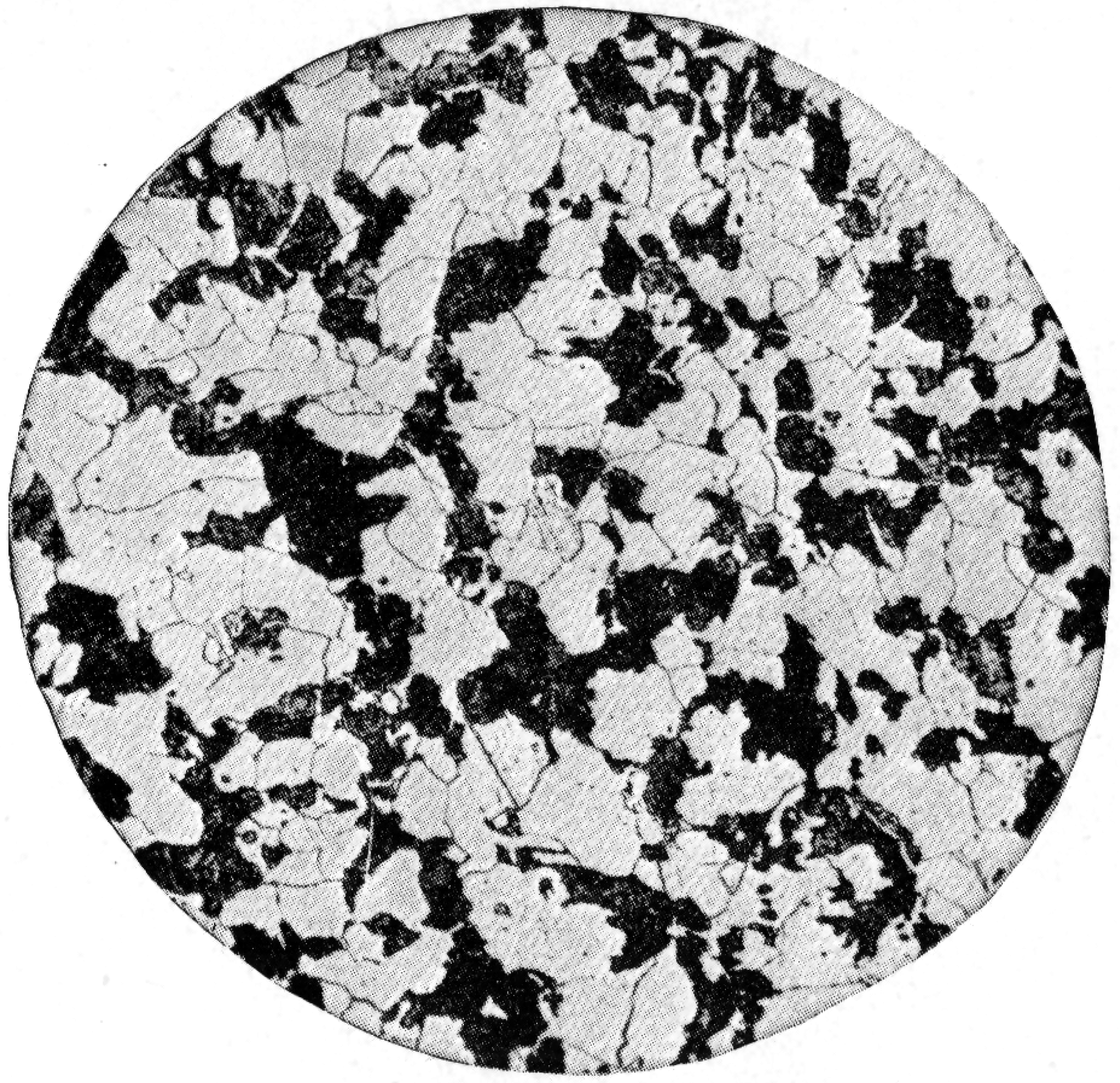

FIG. 6–8. Same steel annealed at 1700F and furnace-cooled. ×25. (Courtesy of Mr. Herbert Blosjo, Metallurgist, Minneapolis Electric Steel Castings, Minneapolis, Minn.)

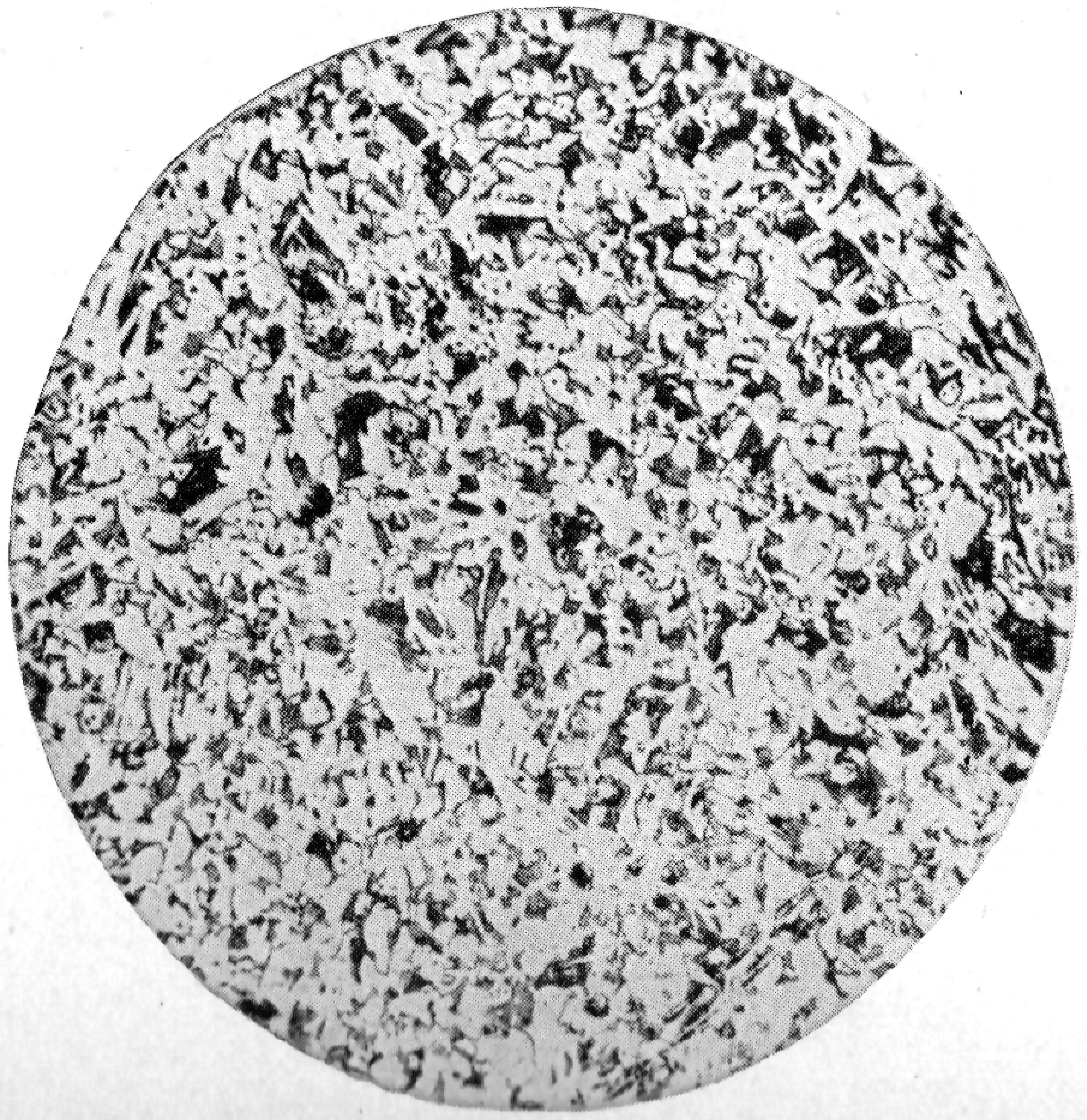

FIG. 6–9. Same steel casting normalized at 1700F and air-cooled. ×100. (Courtesy of Mr. Herbert Blosjo, Metallurgist, Minneapolis Electric Steel Castings, Minneapolis, Minn.)

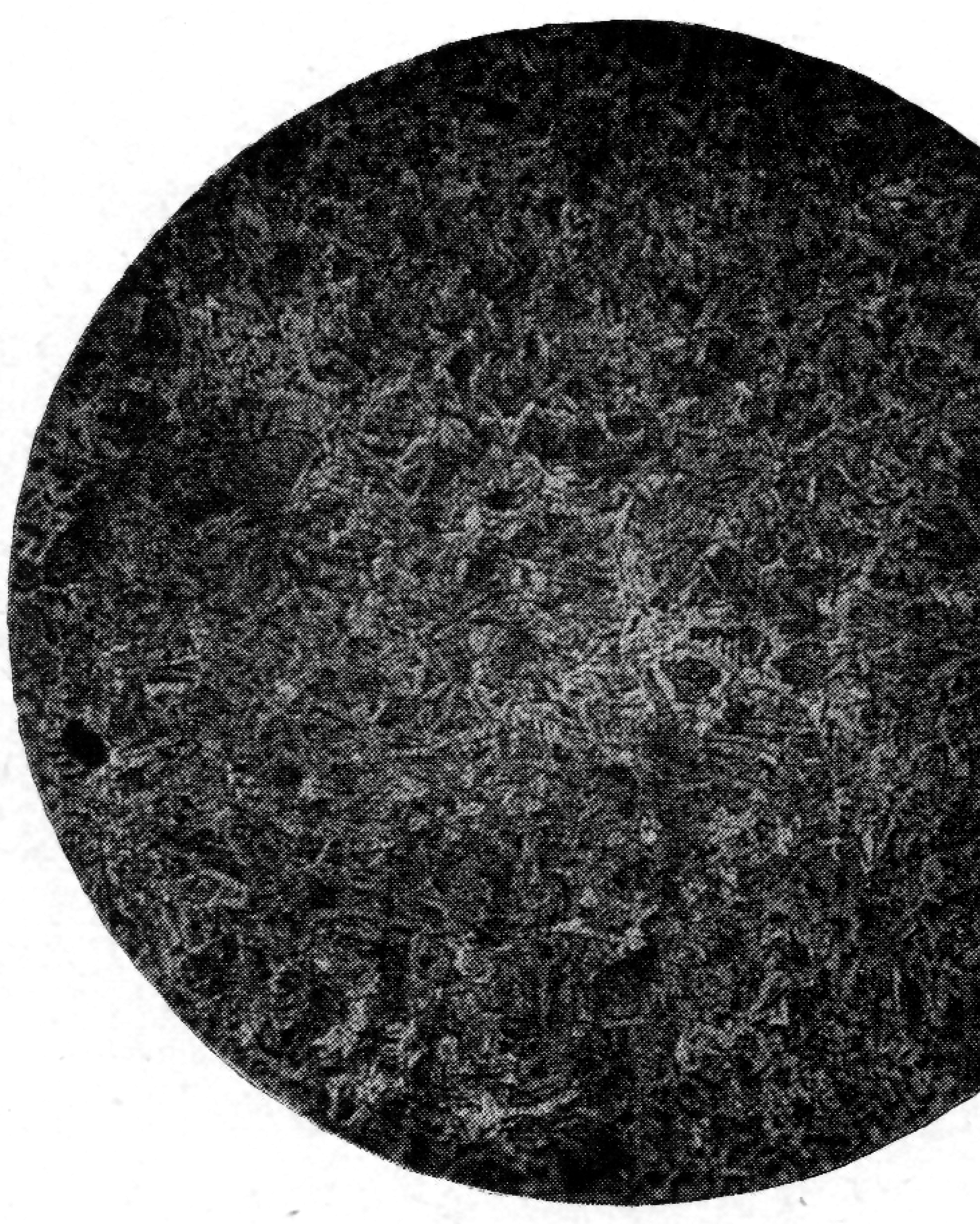

Fig. 6–10. Same steel after quenching in oil from 1650F and tempering at 1300F. ×25. (Courtesy of Mr. Herbert Blosjo, Metallurgist, Minneapolis Electric Steel Castings, Minneapolis, Minn.)

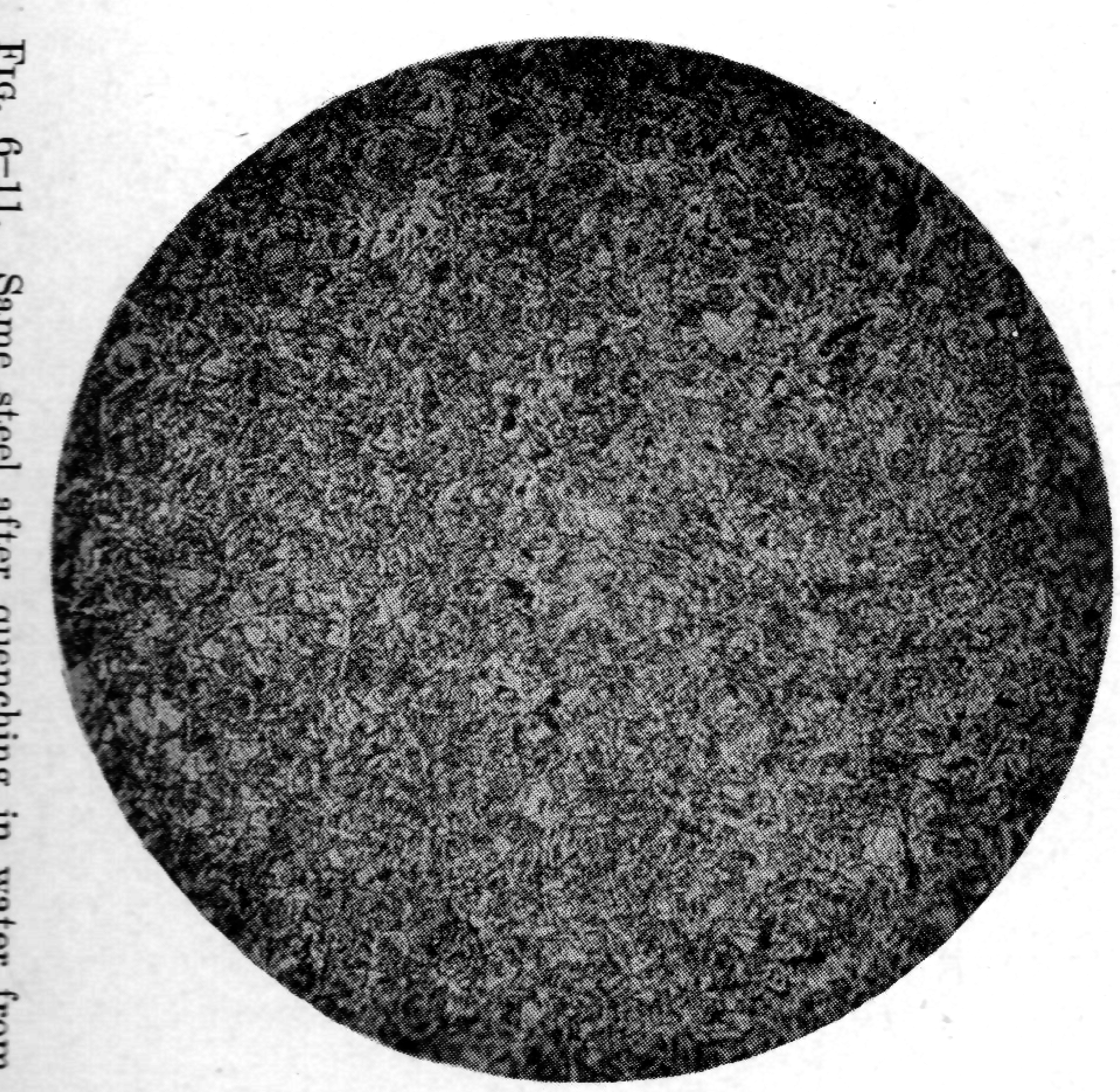

Fig. 6–11. Same steel after quenching in water from 1650F and tempering at 1300F. ×25. (Courtesy of Mr. Herbert Blosjo, Metallurgist, Minneapolis Electric Steel Castings, Minneapolis, Minn.)

TABLE 6–12

Composition and Mechanical Properties of Cast Steels*

Composition and Mechanical Properties	Carbon Steel			Alloy Steel	
	Low	Regular	High	Low	High
Chemical combinations (per cent):					
Carbon	Less than 0.20	0.20–0.40	More than 0.40	0.10–1.00	0.06– 1.70
Manganese	0.50–1.00	0.50–1.00	0.50–1.00	0.50–3.00	10.00–14.00
Silicon	0.02–0.75	0.20–0.75	0.20–0.75	0.20–2.75	1.00– 3.00
Phosphorus	0.05 max.	0.05 max.	0.05 max.	......	......
Sulphur	0.06 max.	0.06 max.	0.06 max.	......	......
Chromium	......	......	......	0.35–6.50	8.00–35.00
Nickel	......	......	......	0.25–5.00	1.00–65.00
Vanadium	......	......	......	0.10–0.65	0.20– 4.00
Molybdenum	......	......	......	0.20–1.00	0.50–17.00
Tungsten	......	......	......	0.75–1.50	0.50–12.00
Copper	......	......	......	0.15–2.75	0.15– 8.00
Cobalt	......	......	......	......	0.50– 4.00
Mechanical properties:					
Ultimate tensile strength, psi	40,000–80,000	60,000–130,000	70,000–140,000	70,000–240,000	40,000–250,000
Yield point in tension, psi	15,000–45,000	30,000–100,000	35,000–120,000	40,000–190,000	25,000–180,000
Elongation in 2 in., per cent	13–36	6–40	1–30	1–35	0–75
Reduction of area, per cent	15–65	3–65	0–55	3.5–72	0–75
Brinell hardness number	90–143	130–325	156–500	140–500	To 680
Impact resistance, ft lb, Izod	15–40	17–50	......	2–77	1.0–100
Charpy	......	11–34	3–10	2–50	......

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* *Cast Metals Handbook* (3d ed.), AFA, Cleveland.

The response of steel to any heat treatment is a direct function of the principal constituent—carbon. Substantially, the only result of annealing the low-carbon type is an increase in its resistance to impact or dynamic stress resulting from the elimination of the Widmanstatten structure and a refinement of the crystalline grains. However, the heat treatment of castings in the medium- and high-carbon range makes possible a substantial improvement in the tensile strength, yield point, and hardness; but with a normal reduction in the elongation and reduction of area. See Chapter 10 for a discussion of heat-treating processes and results.

In addition to the microscope, foundry techniques have been guided and improved greatly by the increasing application of X-rays and gamma rays for the detection of internal shrinkage or cooling cracks and gas inclusions. The magnetic flux method is also employed for the detection of surface and shallow subsurface defects.

6–12. Alloy Steel Castings. When the total amount of any alloying element produces a desired improvement in mechanical or chemical properties, the casting is considered as alloyed. This is regarded as a fair basis for differentiating between plain carbon and alloy steel castings. Accordingly, when only small residual amount of the alloying elements are present, such as nickel, chromium, molybdenum, etc., the casting should not be classified as an alloyed casting.

Alloy steel castings are generally classified as low-alloy and high-alloy. When the total sum of the alloy elements is less than 8 per cent, the alloy is called low-alloy. High-alloy castings contain 8 per cent or more of alloying elements.

A substantial proportion of the total output of steel castings is alloyed irons having properties not obtainable with plain carbon steels, such as heat and corrosion resistance, or high strength combined with high ductility at high or low temperature.

The elements most frequently added for these purposes are nickel, chromium, manganese, molybdenum, vanadium, copper, and silicon. Their particular effects are summarized in the following material.

Nickel. Nickel is one of the first and most useful of the alloying elements. It is soluble in iron in all proportions in both the liquid and the solid state. It is not a carbide-forming element. In an alloy, it strengthens the ferrite matrix by producing fine grains, and refines the pearlitic areas without increasing hardness or impairing either machinability or ductility. For heat-treatable steels, it makes possible deeper hardness with slower cooling rates than can be obtained with plain carbon steel. It is most commonly used in combination with other elements which are usually carbide forming. In the low-carbon alloy steels, it is added in amounts ranging from 0.50 per cent to less than 5 per cent.

Nickel cast steels of various analyses find a wide application for mining machinery, locomotive frames, excavating and steel mill machinery, and marine equipment. They possess a high degree of impact resistance at low temperatures and a high yield-tensile strength ratio.

Chromium. In contrast to nickel, chromium is a relatively potent carbide-forming element and is one of the most popular alloying elements used in steel. In the presence of carbon, chromium forms carbides which, like iron carbides, increase hardenability. Since hardness is a function of the amount and distribution of carbides, the proper ratio of carbon and chromium is significant. In low-alloy cast steels the chromium content ranges from 0.50 to 7 per cent. The lower chromium steels are recommended for use where high strength and abrasion resistance are of primary importance, while the higher chromium steels are recommended for types of service where temperature and corrosion resistance are required. Nickel and chromium are frequently used together in the low- and high-alloy castings. Low-chromium steel castings (less than 1 per cent Cr) find applications where moderately high strength and wear resistance are required. Medium grades (2 to 3 per cent Cr) are well suited for rock-crushing parts and dipper and dredge teeth. Higher grade chromium castings (4 to 7 per cent Cr) find applications where corrosion and excessive oxidation at elevated temperatures must be resisted.

Manganese. Manganese added in amounts exceeding 1 per cent is considered as an alloy. In addition to its excellent role as a deoxidizer and its aid in converting sulphur into the relatively harmless manganese sulphide (MnS), manganese imparts both high strength and ductility to steels when added in the range from 1 to 2 per cent. Manganese steels are very responsive to a normalizing heat treatment to which they are generally subjected. Manganese also lowers the critical cooling requirements and thus permits deep hardening at a relatively slow cooling rate.

These medium-manganese steels withstand repeated shocks or dynamic stresses such as are present in pneumatic tool parts, turbine parts, and railway car castings. They are also recommended for wear or abrasion resistance necessary in excavating buckets, caterpillar shoes, tractor treads, etc. (See the section on "High-Alloy Cast Steels.")

Molybdenum. Molybdenum, like chromium, intensifies the hardenability of steels and increases the tensile strength without appreciably reducing the ductility and impact strength. In amounts of less than 0.50 per cent, molybdenum is now added to steel castings of not more than 0.40 per cent carbon to improve their strength properties at elevated temperatures and to render them more resistant to impact shocks. Molybdenum steel castings are widely used for such diversified applications as locomotive and machinery parts subject to shock, and valves, flanges, and pump and turbine casings.

Vanadium. The effect on carbon steel of small additions of vanadium, ranging from 0.15 to 0.25 per cent, is attributed to its influence in refining the austenitic grain size and in strengthening the ferrite matrix. And, since it is a strong carbide-forming element, it improves the hardenability. In small amounts its influence on the hardness is, proportionately, somewhat less than its influence on the tensile strength and yield point, both of which are, however, increased substantially.

Vanadium imparts to steel castings excellent resistance to impact at normal and subnormal temperatures; and, therefore, these castings find their greatest application where such requirements must be met.

Copper. Additions of between 1 and 3 per cent of copper to plain low-carbon steel castings may well be substituted for higher carbon when increased tensile and yield strengths are required. Copper, however, decreases both the ductility and impact resistance of medium-carbon steels, unless they are fully annealed. In steel castings, given a moderately slow cooling from a temperature slightly above 800F, the small amount of copper substantially increases the tensile strength. Copper is partially soluble in ferrite and, by strengthening the matrix, accounts for a relatively high yield-tensile strength ratio.

Copper-bearing cast steels are much used for heavy ship, locomotive, and mill castings.

Silicon. Silicon, like manganese, is added both as a deoxidizer and as an alloying element. Plain carbon cast steels containing from 0.70 to 2.50 per cent silicon are generally classified as alloys. Low-silicon cast steels give good wear resistance for such uses as cams, gears, track, automotive, and tractor castings. Low-carbon steel sheets, containing up to 5 per cent silicon, have applications in the electrical industry where high magnetic induction is required.

The alloying elements are less frequently added individually than in combination, in which case the particular influence of one element is modified by the others.

6–13. High-Alloy Cast Steels. Even an imposing list of low alloys does not adequately meet all industrial demands for castings. Where service conditions require metals to withstand high temperatures and corrosion, as well as to possess a high degree of wear resistance, cast steels known as "high alloys" are produced; they are available in a wide range of compositions. Among the first of these to be commercially produced was a high-manganese alloy named "Hadfield's manganese steel," after Sir Robert Hadfield, who developed it. It is also referred to by its metallurgical name of austenitic manganese steel. Its composition, as usually made, lies within the limits shown in Table 6–13.

As cast, the alloy is relatively soft but brittle because of the precipitation of Fe_3C and other carbides during its slow cooling. To improve its toughness, it is heated to between 1850 and 1940F (to redissolve the carbides) and quenched in water, after which it is used without tempering. The carbides are retained in solution and, at normal temperatures, provide a solid solution of nonmagnetic austenitic steel. Because of the work-hardening characteristics of austenitic manganese steel, it is practically unmachinable except by grinding. After heat treatment it is similar in hardness to a medium grade of gray cast-iron (180–200 Brinell), but its transformation when cold-worked results in a hardness of approximately 500 Brinell.

TABLE 6–13

AVERAGE COMPOSITION OF MANGANESE STEEL

	Per cent
Carbon	1.10– 1.40
Manganese	10.00–14.00
Silicon	0.30– 1.00
Sulphur	0.06 max.
Phosphorus	0.10 max.

TABLE 6–14

ALLOY CASTING ASSOCIATION STANDARD CLASSIFICATION OF CORROSION-RESISTANT CASTINGS

Designation	Nickel (Per Cent)	Chromium (Per Cent)
NC– 4	34–37	13–17
NC– 7	17–20	6–10
C –21	3 max.	26–30
C –22	3 max.	16–20
CN–31	10–12	26–30
CN–33	7– 9	26–30
CN–37	10–12	22–26
CN–39	7– 9	17–21
CN–40	7– 9	18–22
CN–41	10–12	18–22

The rapidity with which the metal hardens under constant impact makes it particularly resistant to severe abrasion and to heavy impact loads. Therefore, it finds extensive use for railroad crossings, frogs, rock crushers, and for dredging and excavating and road scraping equipment.

The metal may, with proper technique, be welded.

Other high alloys consist of chromium and nickel-chromium steels. These castings retain their superior strength at high temperatures and are, therefore, suitable for use continuously up to 1500F. Because they withstand severe corrosive and oxidizing conditions, they are known as stainless alloys. The alloy compositions recommended for corrosion-resistance castings are given in Table 6–14 and those of the heat-resistant alloys in Table 6–15.

TABLE 6-15

STANDARD CLASSIFICATION OF HEAT-RESISTANT CASTINGS

Castings	Nickel (Per Cent)	Chromium (Per Cent)	Carbon (Per Cent)
Group I			
1	59–62	10–14	0.75 max.
2	37–40	17–21	0.75 max.
3	34–37	13–17	0.75 max.
4	24–27	18–22	0.75 max.
Group II			
1	26–30	7–10	0.50 max.
2	23–27	19–21	0.50 max.
3	22–26	10–13	0.50 max
4	28–32	19–21	0.60 max.
5	28–32	29–31	0.50 max.
Group III			
1	3 max.	16–24	0.50 max.
2	3 max.	25–30	0.50 max.
3	3 max.	25–30	1.00–1.80
4	3 max.	25–30	1.80 min.

6-14. Defects in Castings. In common with other production processes, particularly those which depend largely on manual manipulations, parts produced by casting require continual and careful control over all the elements which enter into their production, in order to obtain internal soundness, clean surfaces, and acceptable tolerances, and in order to reduce unnecessary machining.

One of the most common defects in castings arises largely from improper and inadequate venting of molds. This results in the entrapping of gases which, since they are insoluble in solid metal, constitute blowholes or small smooth-walled cavities found commonly in the center of large sections. This type of defect is largely controllable by avoiding the inclusion of highly oxidized metal in the charge, by pouring at higher temperatures, and by providing for the escape of gases.

Another defect is caused by the shrinkage when the metal is solidifying, or when a small section cools relatively quickly and tends to pull away from a heavier section that is cooling more slowly. This type of defect is readily differentiated from a blowhole, in that it is more irregular in shape. Shrinkage defects are principally caused by faulty pattern design, which may be avoided by eliminating unbalanced sections from a casting so as to provide a more uniform cooling rate. Certain metals also have a greater propensity toward shrinkage defects because of their hot shortness and high shrinkage. A typical condition favorable to a shrink defect is shown in Fig. 6-12. Compare with Fig. 6-13.

When metal is poured into a mold at too low a temperature, too slowly, or through inadequate gates, it fails to combine properly with the preceding layer of metal, and, consequently, forms a fold or a *cold shut,* also known as a *misrun.* The remedy for this defect is obvious. Tears or cracks are other defects found in castings, for which a poor design is responsible.

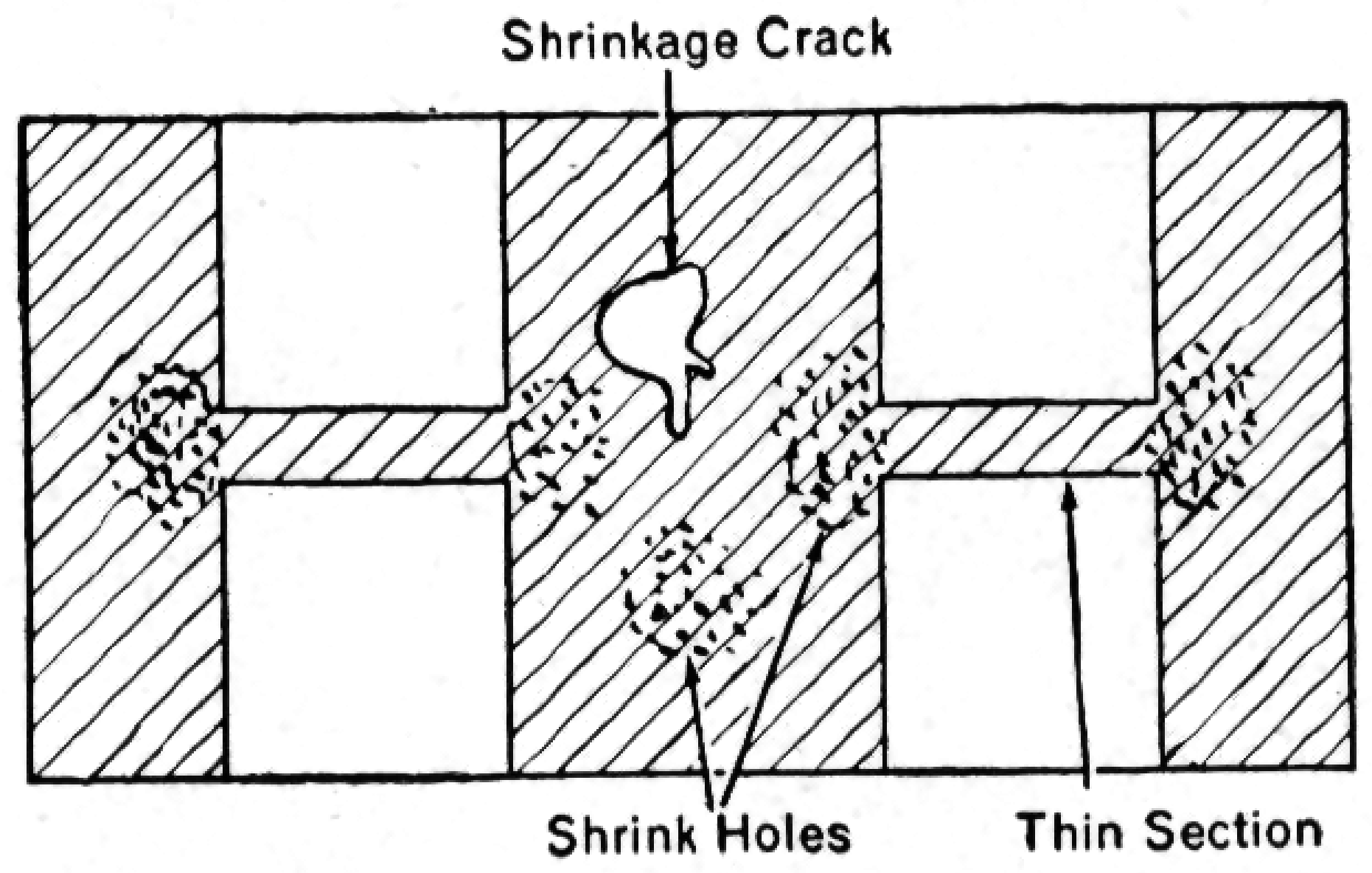

FIG. 6-12. Poorly designed casting. No provision is made for fillets; and heavy sections are connected by too light sections, causing shrinkage cracks and shrink holes.

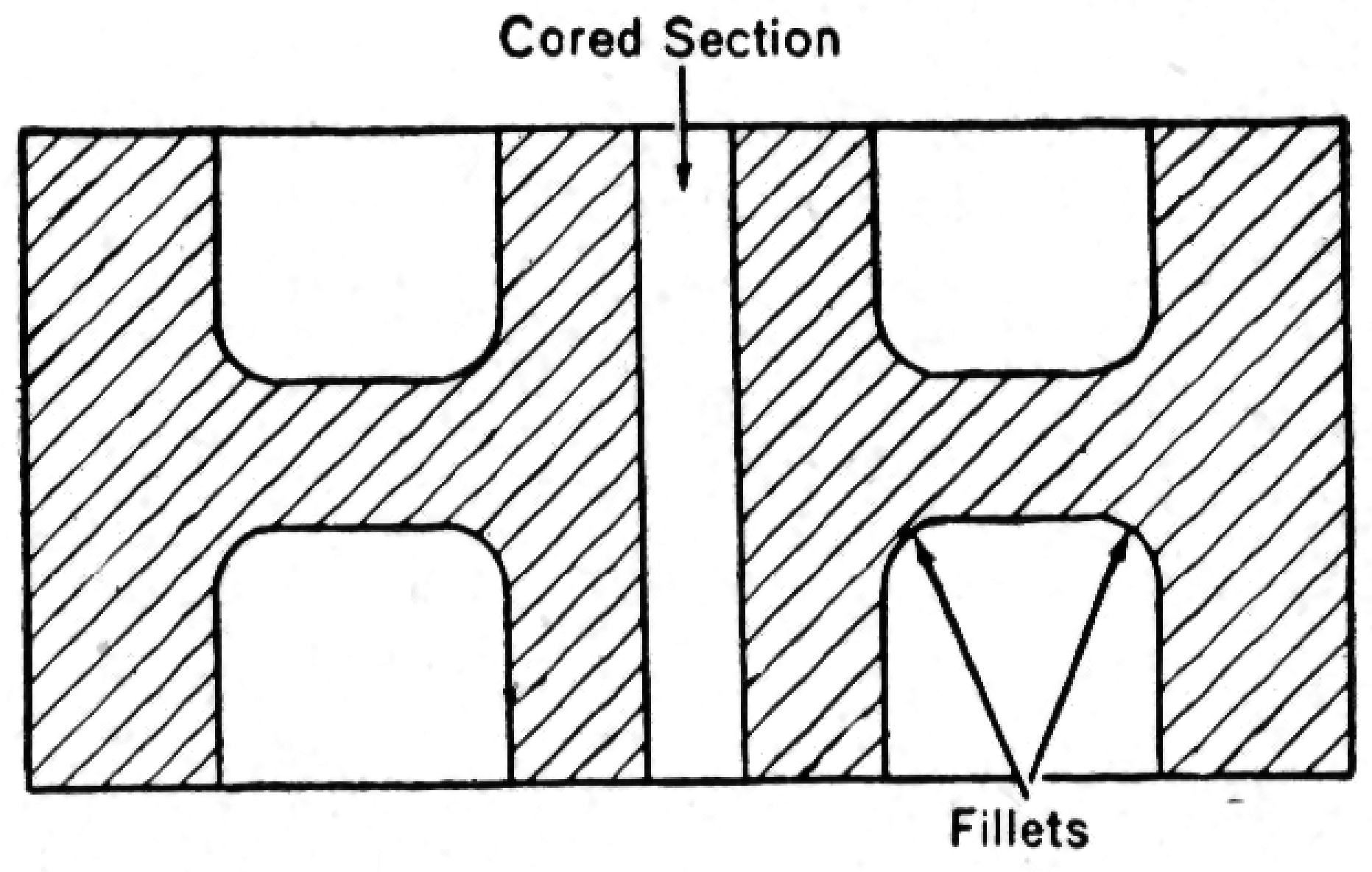

FIG. 6-13. A well-balanced casting, provided with ample fillets.

This type of defect is induced by various forces acting on the casting as a result of unequal cooling rates within various sections during and after solidification. By means of good foundry techniques, this defect can be avoided in spite of a poorly designed casting.

It cannot be emphasized too frequently or too emphatically that production, quality, and economics involved in manufacturing parts are closely interrelated with proper design, selection of materials, and the suitability of the production process. This objective can best be achieved by close cooperation and consultations between the engineering and the production departments or between the designing engineer and the foundry engineer.

QUESTIONS AND PROBLEMS

1. Classify ferrous castings.
2. Compare a cupola and a blast furnace as to size, materials charged, products, shape, functions, furnace atmosphere.
3. What constitutes a "burden"?
4. Trace the passage of materials charged into a cupola and indicate chemical changes in their composition.
5. Discuss the factors which differentiate gray cast-iron and steel.
6. What is meant by "pearlitic" iron?
7. Define "combined" and "free" carbon.
8. In what form is the carbon in chilled cast-iron?
9. Give reasons for the high compressive-tensile strength ratio of gray cast-iron.
10. Assume test bars of unit area machined from gray cast-iron of the following as-cast size: 4 in., 2.75 in., 1.50 in., and 0.50. Place in order of decreasing tensile strength and hardness. Give reasons.
11. List all factors by which high strength cast-iron can be produced.
12. What is the role of alloying elements in gray cast-iron?

13. Discuss the influence of cooling rate on the microstructure of each part of a flywheel of the following dimensions: hub 8 × 12 in., spokes 3 × 4.5 in., rim 3 × 8 in.
14. Compare castings in general to parts of similar composition in the wrought condition.
15. Give reasons for the malleability of malleable cast-iron.
16. What is the form of carbon in malleable cast-iron?
17. Why is the fusion welding of malleable cast-iron not recommended? Explain.
18. Select a machine part for which each of the following metals is most suitable: cast-iron, malleable cast-iron, steel casting, zinc-base die-casting. Select a metal to be used for the following machine parts: coupling for freight cars; heavy ship anchor; frame for a locomotive; impeller for a washing machine; auto cylinder block; base for an engine lathe; pipe fittings for a hydraulic high pressure; high-pressure system.
19. Steel castings generally contain a higher percentage of Mn and Si than wrought steels of otherwise comparable analysis. Explain why.

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CHAPTER 7

MANUFACTURE OF WROUGHT STEELS

7–1. Introduction. The application of castings to all engineering requirements is obviously restricted by their relatively low physical properties as well as by mechanical production difficulties. Many essential products cannot be produced in the required lengths and sizes in any way other than by rolling or forging ductile steels of suitable size and shape.

In this chapter a brief study will be made of the processes used in the production of steels suitable for these uses.

The term "steel" applies in this text to an iron-base alloy consisting of the essential element, carbon, in an amount not to exceed its solubility limit of 1.70 per cent, with small amounts of manganese, silicon, phosphorus, and sulphur. Alloy steels, in addition, contain other elements in varying percentages.

The operation of converting pig iron into steel is essentially one of regulating the percentage of carbon and reducing to the allowable limits the amount of phosphorus, sulphur, and other impurities. Apart from the primitive attempts, the processes now employed to produce steel first appeared in the following order: crucible, Bessemer, open-hearth, electric-arc, and induction.

7–2. Crucible Process. In the crucible process, pieces of wrought iron or steel scrap of small and uniform size are packed in crucibles with pea-size hardwood charcoal and ferromanganese. Alloying elements may also be added when so desired. The crucibles are made of graphite and silica sand, bonded with clay molded to shape, and baked dry. They hold up to 100 lb. When properly filled and sealed, they are heated in a gas-fired furnace (shown in Fig. 7–1) to a temperature at which the metals are thoroughly melted. After they are held for a short time at temperature, the pots are then lifted with tongs, the cover is removed, and the metal is teemed or poured into square ingot molds about 4 in. in diameter and 36 in. high. These ingots are later rolled or hammered into tool steel bars.

The output of a crucible furnace is 6 heats of 30 pots each 24 hr. If each pot contains 100 lb, the production per furnace per 24 hr will be 18,000 lb. The average yield of ingots, however, is slightly less than this.

In view of the small production available, the crucible process has largely been supplanted by the electric-arc furnace process for producing tool steels. However, excellent plain carbon and alloy steels can be produced efficiently in small quantities by this method, although somewhat

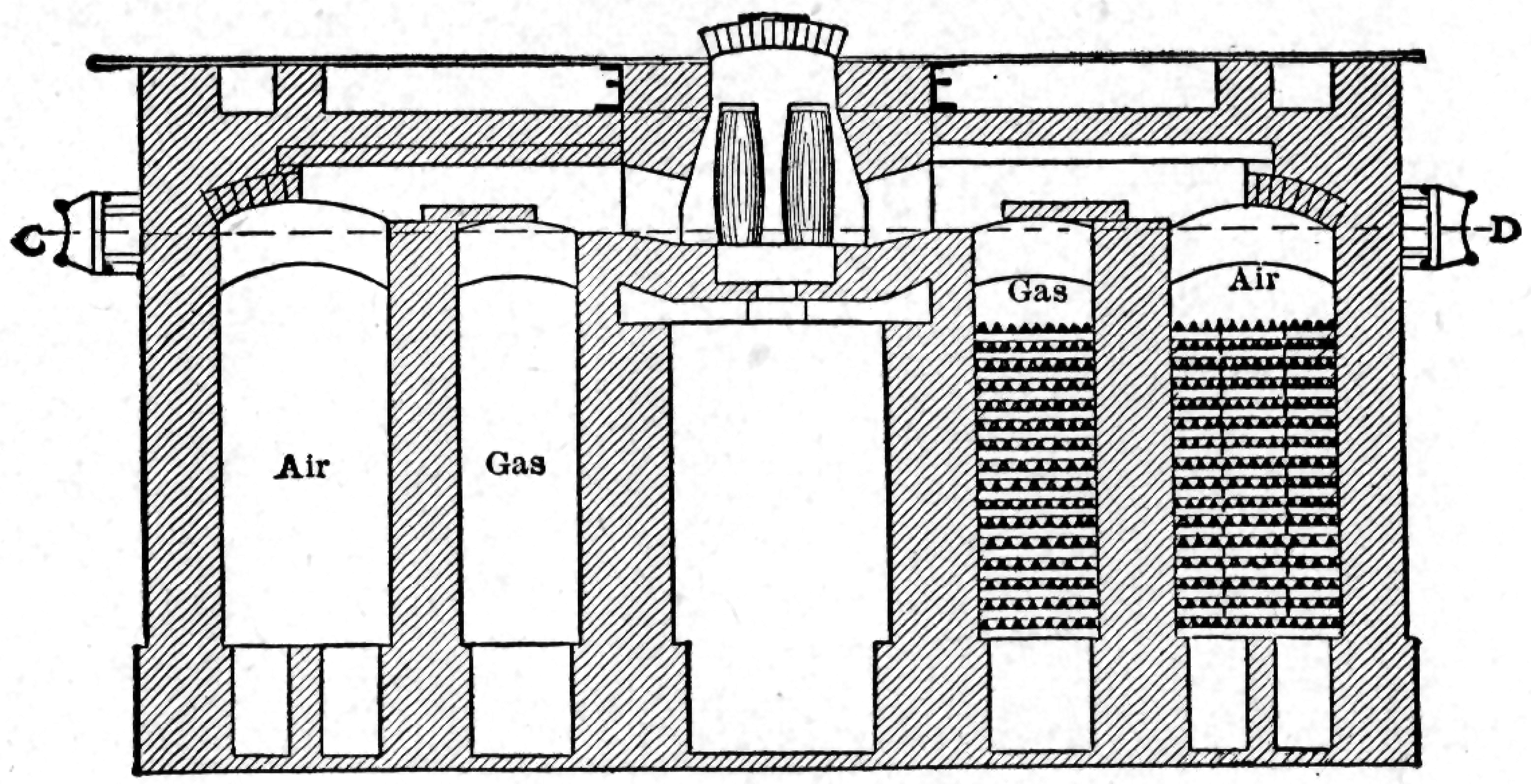

FIG. 7–1. Crucible furnace.

more expensively. Since it involves no complicated chemical reactions during the melting of the charge, the chemistry of the crucible process is comparatively simple. The raw materials are carefully selected.

7–3. Bessemer Process. This process was invented in England about 1856 by Sir Henry Bessemer, after whom it has since been called. The process consists of blowing air through molten metal, transferred from the blast furnace, in a pear-shaped vessel called a converter, shown in Fig. 7–2.

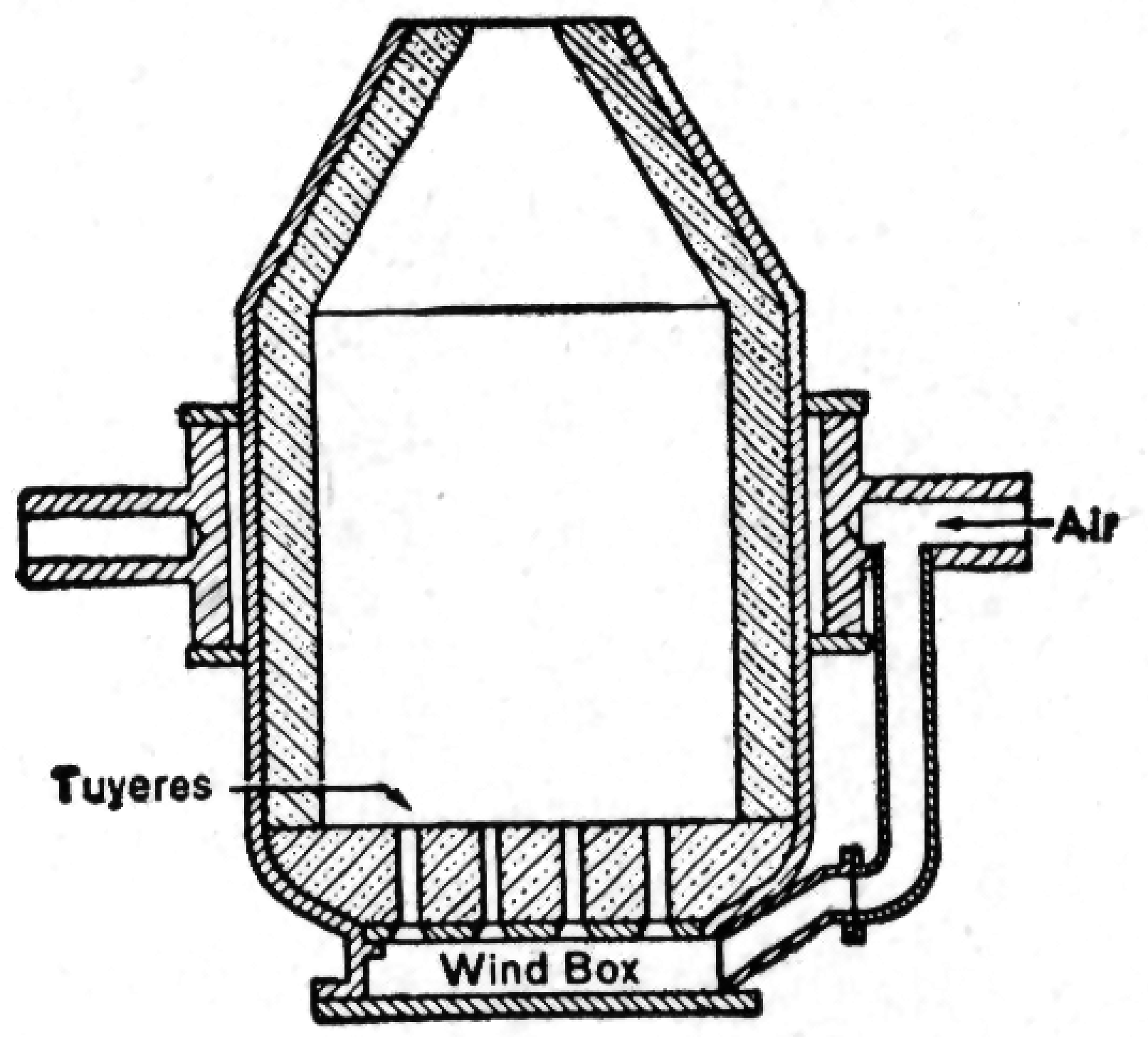

FIG. 7–2. Cross-section through Bessemer converter.

The converter is a large vessel about 18 ft in length and 12 ft in diameter, with a capacity of 10 to 25 tons. It is made of heavy steel plates and lined with siliceous refractory material which withstands an average of 800 heats.* The vessel is suspended above the floor on hollow trunnions, which rest on bearings fitted on heavy cast-iron columns. To one trunnion is attached the gear mechanism for tilting the converter when it is charged and discharged. Through the other trunnion, air is led from the blast line to the wind box in the bottom of the converter and thence through about 20 cylindrical tuyere bricks into the furnace. In each of these bricks are about 12 holes or tuyeres ½ in. or ⅝ in. in diameter, through which about 30,000 cu ft of cold air per minute is forced at a pressure of 25 to 30 psi through about 20 in. of molten metal.

The charge for a Bessemer converter must be molten metal. This is furnished from a ladle drawn from a hot metal mixer, which in turn is supplied by the blast furnace. Since this mixing vessel may contain the *casts* of several furnaces, it serves both as a reservoir and as a mixer from which metal of greater uniformity of composition may be obtained for the converter. The temperature of the metal is held between 2800F and 2900F.

The basis of the refining of iron by this process is the strong affinity of oxygen for manganese, carbon, and silicon—elements which are present in the molten metal. If sufficient oxygen is furnished, it is then possible to oxidize these to form slags or gases.

Immediately upon turning on the blast, with the vessel in an upright position, a reaction starts which eventually converts some of the iron to ferrous oxide: $2Fe + O_2 \rightarrow 2FeO$ and heat. Since FeO is soluble in molten iron, it effectively aids in oxidizing the silicon, manganese, and carbon in this respective order, as shown by the equations:

$$\begin{aligned}
&(1)\quad 2FeO + Si \rightarrow 2Fe + SiO_2 \text{ (slag)} + \text{heat}\\
&(2)\quad FeO + Mn \rightarrow Fe + MnO \text{ (slag)} + \text{heat}\\
&(3)\quad FeO + C \rightarrow Fe + CO \text{ (gas)} + \text{heat}
\end{aligned}$$

These reactions are the essence of the process. As all reactions are exothermic, it is sometimes necessary to cool the metal before it is poured from the converter. This is done by blowing steam through it or by making additions of cold scrap metal.

While conditions vary according to plant practices, the approximate analysis of the metal used is given in Table 7–1.

TABLE 7–1

AVERAGE ANALYSIS OF A BESSEMER CHARGE (PER CENT)

Carbon	4.00–4.50
Manganese	Less than 0.70
Silicon	1.00–1.75
Phosphorus	0.08–0.10
Sulphur	0.05 max.

At the end of the blow, which usually lasts from 10 to 20 min, the analysis of the iron is approximately as shown in Table 7–2.

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* The bottom of the converter is removable and, because of erosion by the molten metal, is replaced by a new one after 25 to 35 heats.

TABLE 7–2

Approximate Analysis of Bessemer Steel before Recarburizing (Per Cent)

Carbon	0.03
Manganese	0.01
Silicon	0.005
Phosphorus	0.100
Sulphur	0.045

As the siliceous lining and acid slag of the American Bessemer practice are not conducive to the removal of the phosphorus and sulphur, these not only remain unaffected but are slightly concentrated or increased as a result of the elimination of the silicon, manganese, carbon, and some of the iron. It is imperative, therefore, that these two elements be kept to the lowest practical limits in the charge.

When, by the appearance of the flame issuing out of the mouth of the converter, the "blower" judges* that the carbon has been almost completely eliminated, the vessel is again tilted and the metal is discharged into a ladle where it is *recarburized*, i.e., additions of carbon in the form of molten pig iron, crushed anthracite, coke, or either molten or cold ferromanganese are made to meet the required specifications and to complete the deoxidation of the metal. Other additions may be made at this time to produce steels with special characteristics. After the additions have been thoroughly incorporated, the metal is then teemed or cast into ingot molds in a manner common to all the other processes.

The production of approximately 25 tons of steel from molten iron in the space of 10 to 20 min implies that reactions proceed very rapidly and violently in the converter. This fact increases the difficulty of control over the composition, and results in some variation between heats of Bessemer steel. And, because of the high percentage of the residual phosphorus content as shown in Table 7–2 (0.04 per cent maximum in good steel), this steel is unsuited for service where high dynamic stresses prevail.

Nevertheless, the Bessemer process fulfills an industrial need for the economical production of low-carbon steels (less than 0.20 per cent) suitable for skelp (welded pipe), sheet metal, reinforcing rods, track spikes, and wire for screws and nails, and of special high-sulphur steels for automatic screw machine work.

Because of the economy and rapidity with which Bessemer steel is produced, the process at one time ranked first in the quantity of steel produced. The increased emphasis on higher and more uniform quality has reduced it to second rank in respect to total steel production, and to fifth in respect to quality of its product. Yet, the substantial total of approximately 6,000,000 tons of Bessemer steel is produced annually in the United States, an amount exceeded only by basic open-hearth production.

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*Photoelectric-cell methods of determining the end point are now being used in some plants.

7–4. Open-Hearth Process. Since Bessemer's discovery, the only process destined to surpass it in importance both as to quality and quantity developed out of the practical application of the regenerative principle of heat conservation, the basis for the success of the open-hearth furnace. Over 90 per cent of all steel is produced by the open-hearth process.

The type of refractory materials, which constitute the lining of the furnace and which contact the slag and the metal, identifies the process as either acid or basic. If an acid refractory (silica, SiO_2) is used, the slag which blankets the molten metal must be predominantly siliceous; if basic magnesite ($MgCO_3$), calcium carbonate ($CaCO_3$), or dolomite $(CaMg)CO_3$ are used, the slag also must be predominantly basic.

The acid open-hearth process is relatively unimportant from a tonnage standpoint in the United States, producing less than 1 per cent of the total steel production. As no phosphorus is eliminated in this type, pig iron made from ores characteristically high in this element cannot be used. However, steels of the highest quality are produced for many diversified uses and exact specifications. The charge for an acid furnace consists of scrap steels and low-phosphorus pig iron, which vary in proportion over wide limits. As in the Bessemer process, the manganese, silicon, and carbon are removed as oxides incorporated in the slag or as gases. The advantages claimed for acid steel are that (1) the metal is less oxidized than basic steel, (2) the slag is more easily controlled and, therefore, more consistently uniform steel is obtainable, and (3) the furnace lining materials cost less than basic materials. Its disadvantage is that only scrap and pig iron with a phosphorus content lower than the allowable limits in the steel can be used.

Except that the acid open-hearth is usually smaller and that the materials of construction are siliceous in their chemical reactions at elevated temperatures, the description given of the basic open-hearth furnace applies to both acid and basic processes.

7–5. Basic Open-Hearth. The open-hearth furnace consists of a horizontal basinlike hearth, enclosed by four walls and surmounted by a roof arranged to throw the products of combustion of the fuel gases over the metal from end to end. At the two ends of the hearth, ports or openings are provided, through which the fuel gases enter the furnace and the exhaust gases leave. Below these ports are the regenerative chambers, made up of layers of bricks placed checkerboard fashion to enable the fuel and air to pass through into the furnace and the hot exhaust gases to pass out into the stack. On the charging-floor side are located vertically sliding doors for loading the furnace. The entire hearth, as high up as the slag line, is lined with basic materials consisting of calcium and magnesium oxides. A furnace of 100-ton capacity is approximately 84 ft long, 26 ft wide, and is built on a foundation of concrete and steel. The hearth is about 48 ft long, 18 to 20 ft wide, and from 2 to 3 ft deep. A cross-section of the furnace is shown in Fig. 7–3.

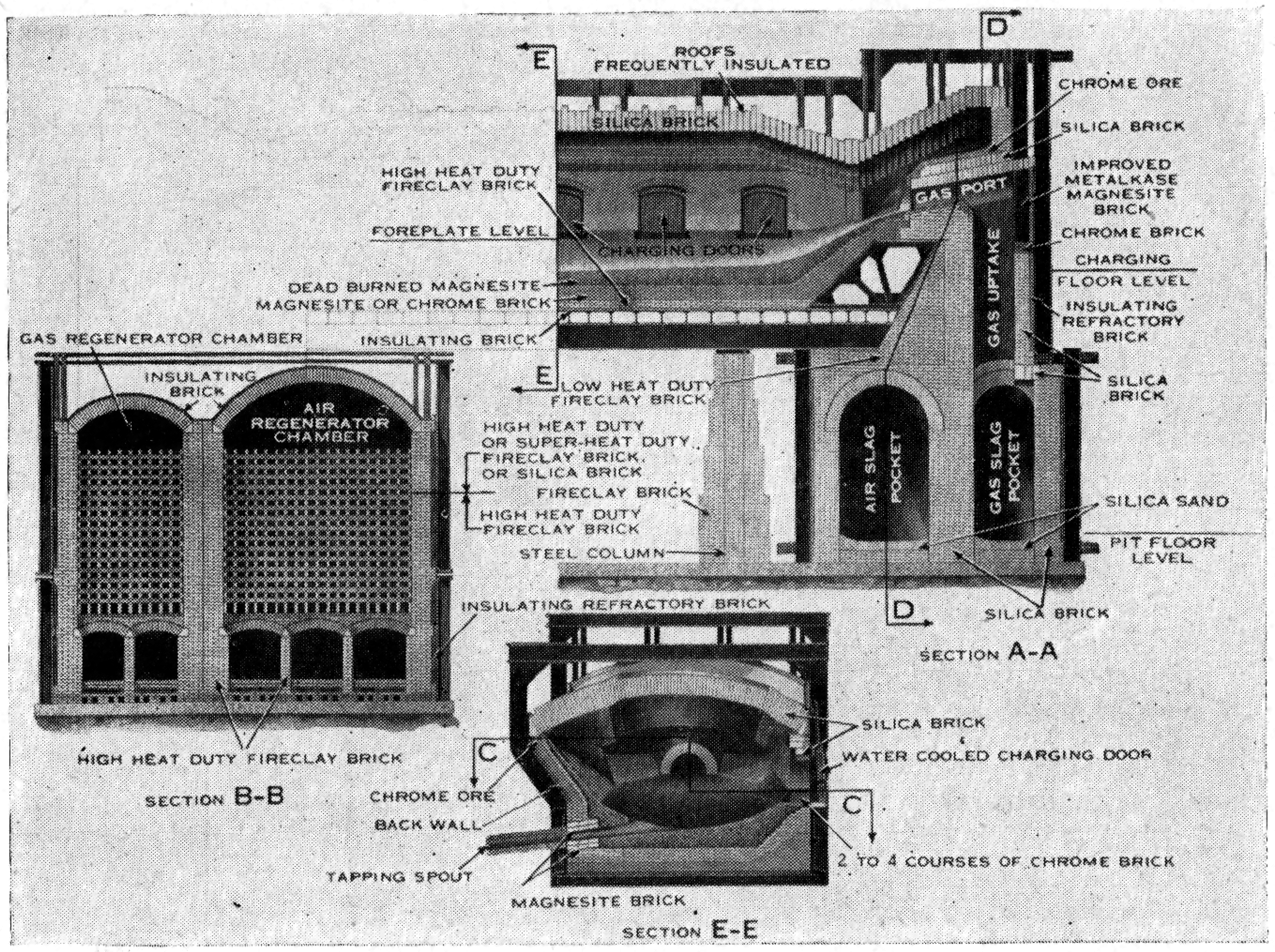
E
ROOFS FREQUENTLY INSULATED
D
SILICA BRICK
CHROME ORE
SILICA BRICK
HIGH HEAT DUTY FIRECLAY BRICK
GAS PORT
IMPROVED METALKASE MAGNESITE BRICK
FOREPLATE LEVEL
CHARGING DOORS
CHROME BRICK
CHARGING FLOOR LEVEL
DEAD BURNED MAGNESITE
MAGNESITE OR CHROME BRICK
GAS UPTAKE
INSULATING REFRACTORY BRICK
GAS REGENERATOR CHAMBER
INSULATING BRICK
E
LOW HEAT DUTY FIRECLAY BRICK
SILICA BRICK
INSULATING BRICK
AIR REGENERATOR CHAMBER
HIGH HEAT DUTY OR SUPER-HEAT DUTY FIRECLAY BRICK, OR SILICA BRICK
FIRECLAY BRICK
HIGH HEAT DUTY FIRECLAY BRICK
AIR SLAG POCKET
GAS SLAG POCKET
SILICA SAND
STEEL COLUMN
PIT FLOOR LEVEL
INSULATING REFRACTORY BRICK
D
SILICA BRICK
SECTION A-A
SILICA BRICK
HIGH HEAT DUTY FIRECLAY BRICK
C
WATER COOLED CHARGING DOOR
SECTION B-B
CHROME ORE
C
BACK WALL
2 TO 4 COURSES OF CHROME BRICK
TAPPING SPOUT
MAGNESITE BRICK
SECTION E-E

Fig. 7–3. Typical basic open-hearth furnace. (Courtesy of Harbison-Walker Refractories Co., Pittsburgh, Pa.)

The open-hearth furnace has been operated with producer gas, natural gas, coke oven gas, fuel oils, tar, pulverized coal, as well as other fuels; the most widely used, however, is producer gas. The furnace capacity varies between 75 and 350 tons* and, ordinarily, from 10 to 12 hr are required to produce a heat of steel.

The success of the open-hearth process must be attributed, at least in part, to the system whereby the fuel and air are preheated before entering the furnace. Preheating is accomplished by having the exhaust gases pass through one set of checkers at the opposite end of the hearth. By thus yielding a considerable amount of their residual or *sensible* heat,

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*The average capacity varies from 100 to 150 tons.

the gases cause the checkers to become progressively hotter. To increase the furnace temperature, the direction in which the fuel and air enter the furnace is alternated between the two sets of checkers every 15 or 20 min. This alternation eventually preheats the air to 2000F. It is thus possible to heat the furnace to almost any temperature desired.

While economic considerations and plant facilities may influence the proportions somewhat, the normal charge for an open-hearth furnace consists of 50 per cent scrap, ore, and limestone and 50 per cent hot metal from the mixer. While practices vary in different plants, a typical cold charge for a 150-ton basic open-hearth furnace consists of approximately 5 per cent raw limestone, 9 per cent ore, 31 per cent selected steel scrap, and 5 per cent pig iron. These are charged into the furnace, in predetermined amounts, in boxes manipulated by an electrically-operated charging machine, in the sequence given above. After these materials are partly melted, in about 2 hr, 75 tons of molten metal from the mixer are poured into the furnace through a spout placed in one of the doors. Provided that the temperature of the furnace at this time is sufficiently high, the introduction of the hot metal produces a vigorous reaction on the hearth, which causes the slag, now covering the melted materials, to foam and swell until it reaches the slag hole in the furnace wall, through which it passes out of the furnace. This slag consists largely of the products of the oxidation of the phosphorus, silicon, and manganese.

At a later period, known as the "working period," samples of the metal are examined for carbon determinations. If the proportion of this element is found too low, more molten iron from the mixer is added; but, if too high, iron ore is thrown in to oxidize it. This period is devoted entirely to controlling the carbon and to obtaining correct basicity of the slag to eliminate the phosphorus. After the unwanted products have been satisfactorily eliminated and the temperature properly adjusted, the finishing period begins, when recarburizers, some deoxidizers, and alloys are added. After these have become thoroughly incorporated, the metal is tapped into the pouring ladle where further additions may be made to increase the carbon and where small amounts of aluminum* may be added to complete the deoxidizing. To avoid high losses, easily oxidized alloying elements are added to the ladle rather than to the furnace.

Fundamentally, the elimination of impurities in the open-hearth proceeds by oxidation, as in the Bessemer process. And, aside from the elimination of phosphorus by the basic slag to form calcium phosphate $Ca_3(PO_4)_2$, the sequence of their removal is the same as in the Bessemer. Because of the greater flexibility of slag control and because of the facility for making required additions and analyses afforded by the open-hearth, steels of higher quality and uniformity are produced for such uses as rails, high-strength wire, rolled structural steel shapes, large castings, boiler plate, strip steel for automobile bodies, etc., and seamless tubing.

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*For fully deoxidized steels only.

In steel plants where all steel-making processes are integrated, the basic open-hearth furnace becomes a valuable adjunct to the acid Bessemer in a practice known as *duplexing*. This practice consists of charging partially refined molten metal from the converter into a basic open-hearth for complete removal of the phosphorus and the carbon. The procedures for slag control, recarburizing, and deoxidizing are the same as when the charge consists of cold scrap.

7–6. Electric-Arc Process. Serious efforts to produce commercial electric furnace steels are of relatively recent date. The constantly mounting demands for steel of even higher quality than the open-hearth can furnish, and in larger quantities than the crucible can, led to the development in the past 25 years of various types of furnaces in which electricity constituted the heating medium.

In contrast to the pneumatic principle of the Bessemer and the oxidizing atmosphere of the open-hearth, a reducing, oxidizing, or neutral condition can be obtained in the electric furnace, and the removal of the impurities can be effected by the heat and the slag. Thus, the proportions of phosphorus, which are eliminated under oxidizing conditions, and of sulphur, eliminated under reducing conditions, are fully controlled in the electric process by regulating the composition of the slag. This inherent flexibility makes possible the production of steel of crucible quality in commercial tonnages.

The most widely used electric furnace is one embodying principles first developed about 1890 by a Frenchman, Paul Louis Toussaint Heroult. Encased in a cylindrical shell of steel about 1 in. thick, the furnace is composed of a saucer-shaped hearth and vertical walls, surmounted by a high-grade silica brick removable roof, as shown in Fig. 7–4.

The refractory material constituting the hearth for a basic furnace is magnesite brick, which conforms to the contour of the hearth. Above the hearth, about 14 in. of fine magnesite that is bonded with sodium silicate or tar is rammed in by layers; this is then *burned in* by the radiated heat of an arc drawn between the vertical electrodes and another placed horizontally on the hearth for the purpose. Just above the slag line, the furnace is lined with silica brick, as in the open-hearth. This is separated from the magnesite basic bottom by layers of a neutral refractory brick. Two rectangular sliding doors, placed 90 degrees apart, provide for charging and working the metal, while a smaller opening with a covered spout is placed on the tapping or pouring side. Three electrodes are inserted through holes in the roof, each forming an apex of an equilateral triangle about a vertical axis. By means of a motor-driven gear mechanism placed underneath, the furnace can be tilted to any angle for tapping and slagging.

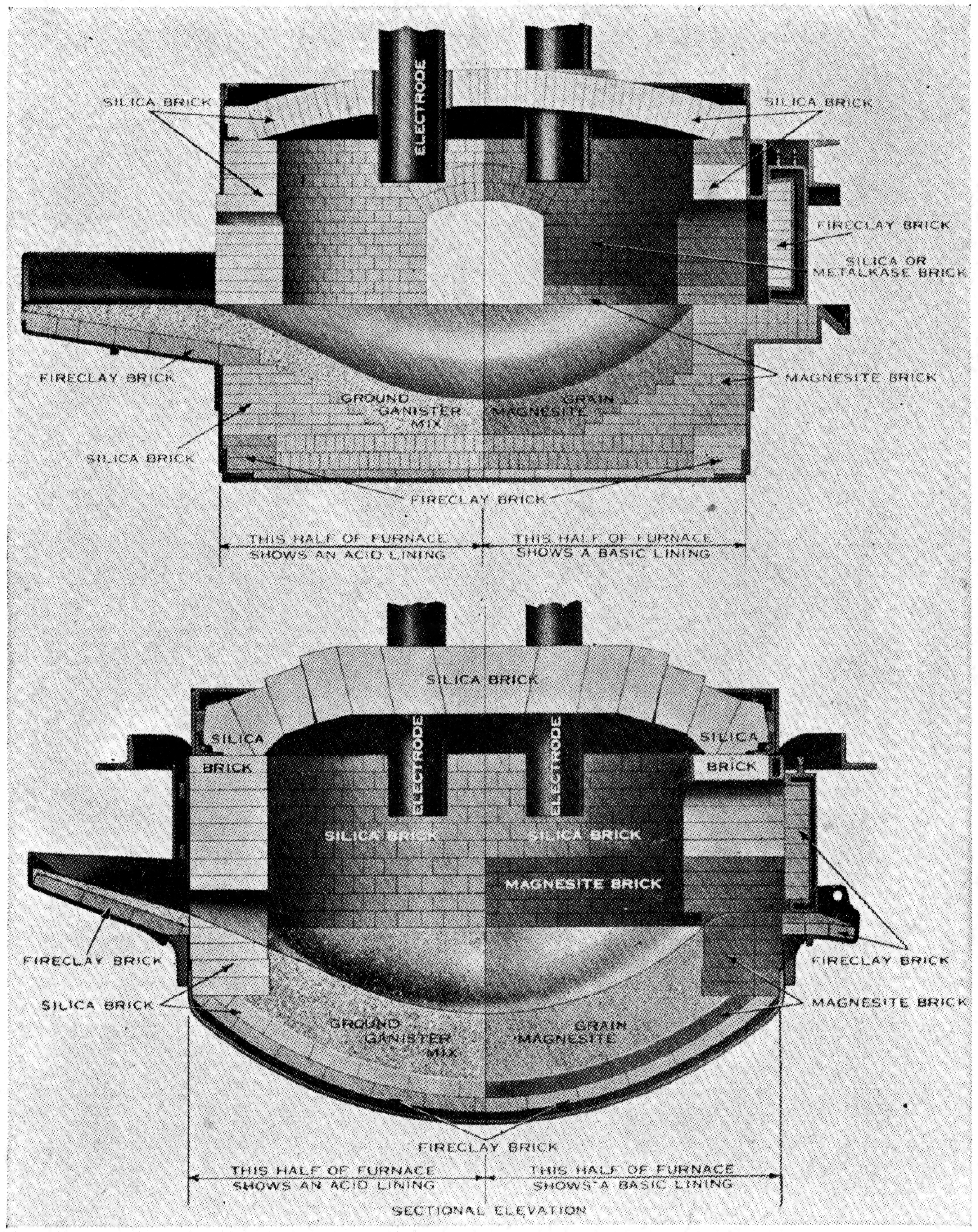
ELECTRODE
SILICA BRICK
SILICA BRICK
FIRECLAY BRICK
SILICA OR METALKASE BRICK
FIRECLAY BRICK
MAGNESITE BRICK
GROUND GANISTER MIX
GRAIN MAGNESITE
SILICA BRICK
FIRECLAY BRICK
THIS HALF OF FURNACE SHOWS AN ACID LINING
THIS HALF OF FURNACE SHOWS A BASIC LINING
SILICA BRICK
SILICA BRICK
SILICA BRICK
ELECTRODE
ELECTRODE
SILICA BRICK
SILICA BRICK
MAGNESITE BRICK
FIRECLAY BRICK
FIRECLAY BRICK
SILICA BRICK
MAGNESITE BRICK
GROUND GANISTER MIX
GRAIN MAGNESITE
FIRECLAY BRICK
THIS HALF OF FURNACE SHOWS AN ACID LINING
THIS HALF OF FURNACE SHOWS A BASIC LINING
SECTIONAL ELEVATION

Fig. 7–4. Typical electric steel melting furnaces.

The maximum ingot capacity of a commercial type basic furnace is 100 tons, although the average size ranges from 40 to 70 tons. Depending on the size of the furnace, from 6 to 10 hr are usually taken to melt and refine a heat of steel. The electrodes are made of bonded amorphous carbon or graphite and vary in diameter from 12 to 20 in., depending on the capacity of the furnace. In order to avoid high-current surges and fluctuating temperatures by changes in the volume of the metal and the consumption of electrodes, the height of the electrodes above the slag or the metal is automatically kept constant. The 3-phase current is led into the furnace through 3 heavy-stranded copper cables, attached to the electrodes through holders; and the metal is heated by the arc formed between the electrodes above the hearth and the metal itself. The charging and tapping sides of a furnace are shown in Figs. 7–5 and 7–6.

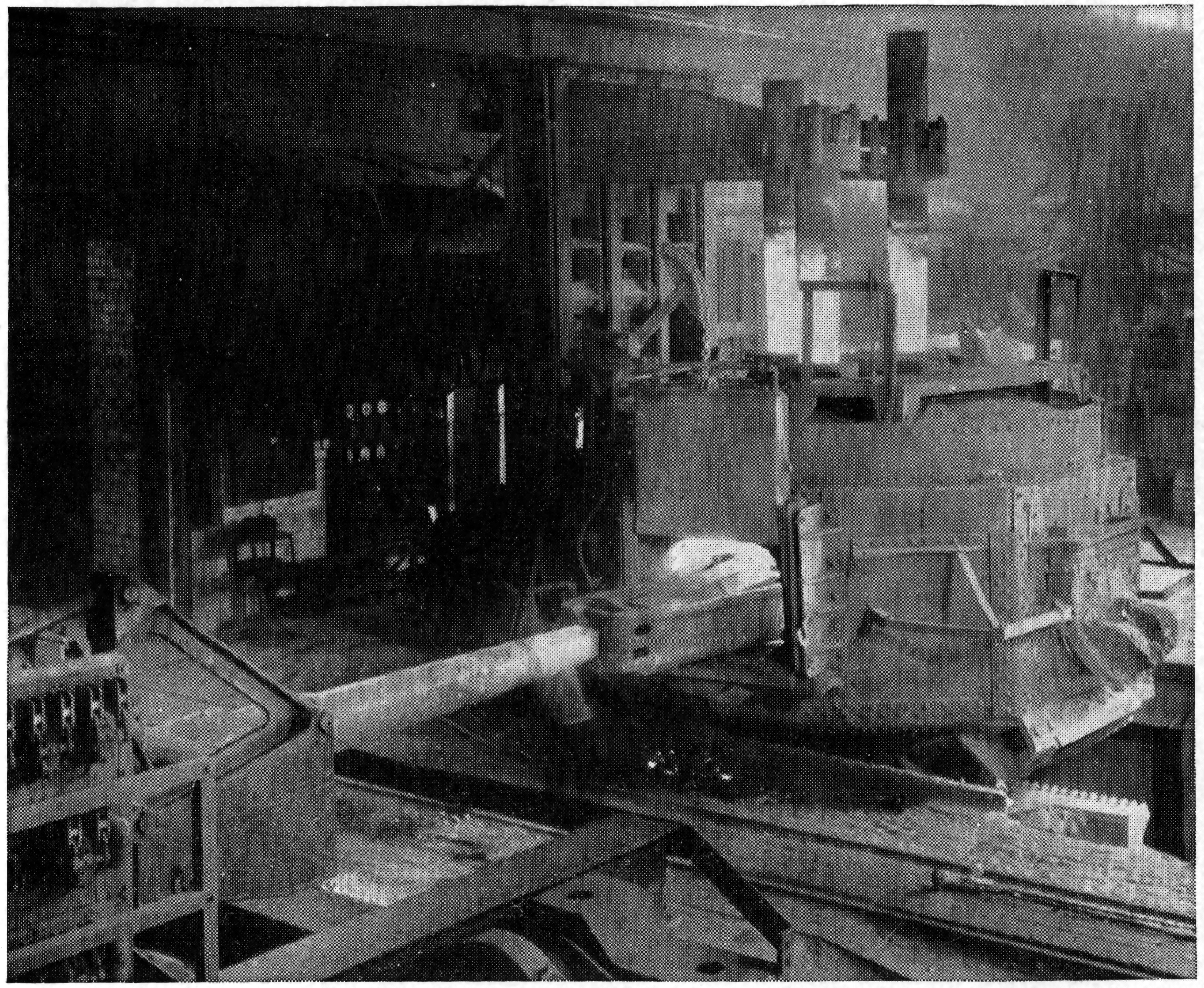

Fig. 7–5. Side-charging an electric furnace.

As in the open-hearth, the electric-arc furnace charge consists of selected steel scrap and molten metal. Refer to Table 7–3. The furnace operates efficiently on either a completely cold or hot metal charge. However, the deleterious results of the combustion of other fuels are not experienced, since the heat for melting the scrap is supplied by an arc drawn between the electrodes and the metal which acts as a common conductor.

When the furnace is charged with cold scrap, the maximum current and voltage are employed to obtain a quick melt and to produce a slag which at this time is made highly basic and oxidizing by the addition of burned lime, fluorspar, mill scale, and silica sand to act as fluxes. If the metal charged into the furnace does not contain more phosphorus than is

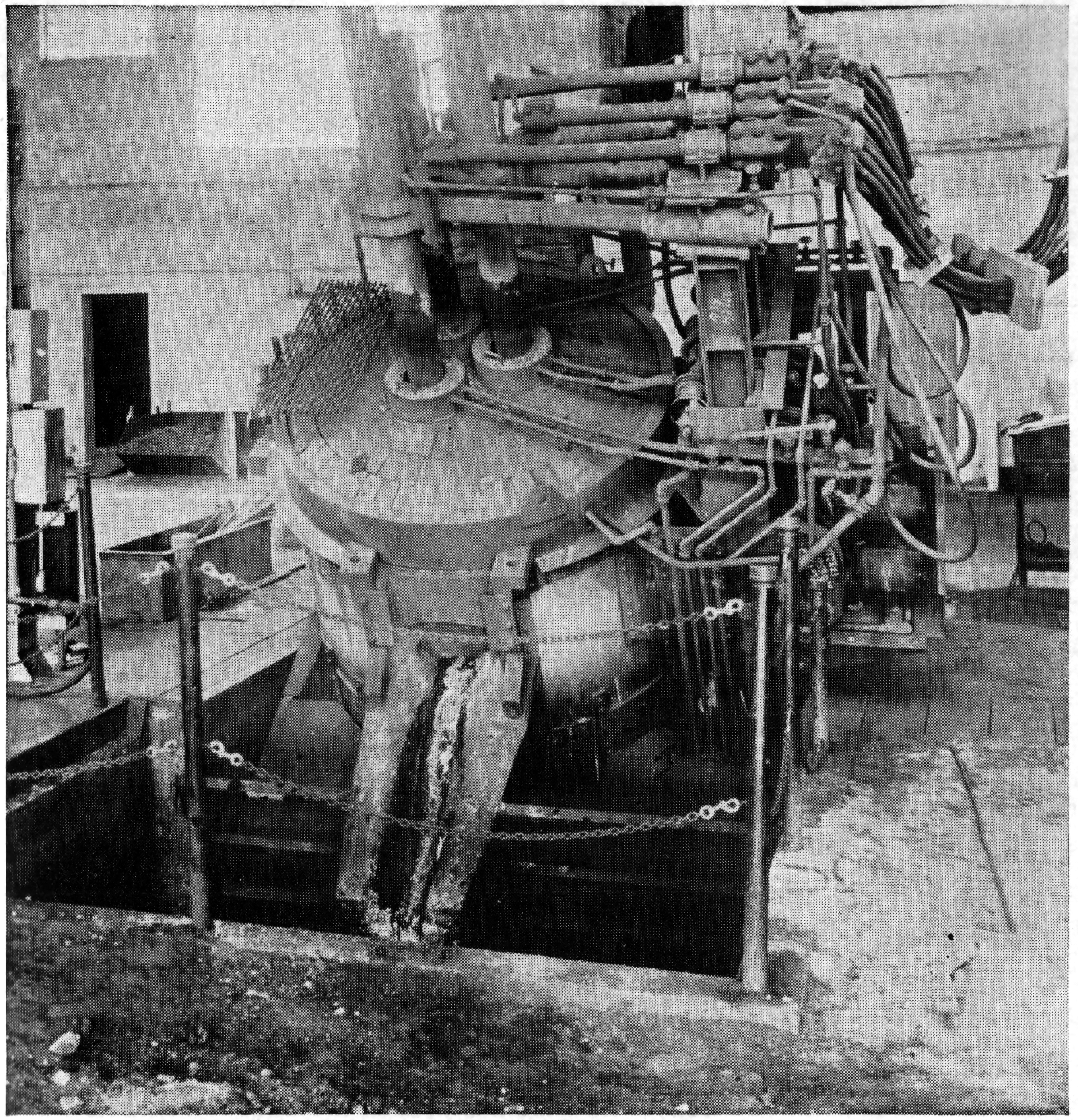

Fig. 7–6. Tapping side of an electric furnace.

TABLE 7–3

Size and Capacity, with Transformer Ratings, for Standard Heroult Electric Furnace

Inside Diameter of Shell	Transformer Capacity KVA	Nominal Charge Scrap Steel (Lb)
7 ft 3 in.	1,000– 1,500	5,000– 6,000
9 ft 0 in.	2,000– 3,000	10,000– 12,000
10 ft 0 in.	2,500– 3,500	16,000– 20,000
11 ft 0 in.	3,000– 4,500	20,000– 24,000
12 ft 0 in.	3,500– 5,000	30,000– 34,000
13 ft 6 in.	5,000– 7,500	36,000– 40,000
15 ft 6 in.	7,500–10,000	60,000– 70,000
18 ft 0 in.	10,000–12,000	100,000–120,000
19 ft 0 in.	12,000–14,000	120,000–150,000
6-electrode elliptical shell 20 ft × 29 ft.	20,000–24,000	200,000–230,000

allowable in the finished product (0.035 per cent), the slag is deoxidized by adding crushed coke or coal, ferromanganese, or ferrosilicon, and the current is reduced. If phosphorus has to be removed, as when hot metal from the Bessemer or open-hearth is used, the first slag is raked off before a new slag of the above materials is made. If a heat of alloy steel is being made, the alloying elements are added at this time. And since the furnace atmosphere and the slag are reducing, the additions are made in the furnace with a minimum loss by oxidation.

After this, the furnace openings are sealed with clay to avoid an oxidizing condition by the admittance of atmospheric air; and the finishing or refining of the heat continues for about 1 hr, or until all elements are thoroughly incorporated. At the end of this period, the furnace is tilted and the metal is tapped into a ladle in a manner similar to other processes.

As already pointed out, the electric-furnace process produces, from cold scrap or raw materials, large quantities of steel comparable in quality to the crucible process. Its product is therefore used for purposes where formerly only crucible steel was available, as well as for many large parts for which the crucible process cannot furnish metal in sufficient amounts. The principal products of the basic electric furnace are high-speed steel and other special alloy steels, and high-carbon tool steels.

The advantages of heating with electricity are: (1) it produces an intense and quick means of heating, (2) none of the contaminating conditions incident to other heating media are encountered, (3) it is the only process in which all impurities are controlled, (4) deoxidation additions may be made in the furnace with only slight loss by oxidation, and alloying elements may be similarly added for the same reasons, (5) the temperature is easily controlled, (6) no impurities are introduced into the steel by the combustion of the fuel, and (7) it provides a method for remelting alloy scrap without excessive loss.

Acid-lined electric furnaces are uniformly smaller in capacity and are employed largely in steel foundries for the production of steel castings.

7–7. Induction Furnace. Another type of electric furnace, devoted largely to the production of stainless alloys and high-speed cutting steel, operates on the principle of electromagnetism. A cross-section of such a furnace is shown in Fig. 7–7.

The furnace is constructed of asbestos lumber surrounding a thin walled open-top crucible, embedded in a finely packed refractory, around which a helix of water-cooled copper tubing functions as a primary conductor for a high-frequency current. The lower part of the furnace shell, as well as the upper portion, are built of firebrick. Attached to the outer shell are trunnions which permit the furnace to be tilted for pouring. For its operation, electric current ranging from 360 to 2,000 cycles per second is passed through the primary coils, while the metal in the crucible constitutes a conductor for the heavy secondary current. This induced current quickly melts the metal in the crucible and produces a vigorous stirring action which thoroughly mixes all ingredients in the charge. A 300-kw furnace will melt down and completely refine 1,000 lb of metal in a little over 1 hr.

It is not a practice to produce and maintain a slag covering on the metal during the melting period in an induction furnace, because it is rendered practically unnecessary by (1) the convexity of the molten bath produced by the electromagnetic forces, (2) the negligible amount of oxidation, and (3) the use of only clean scrap materials.

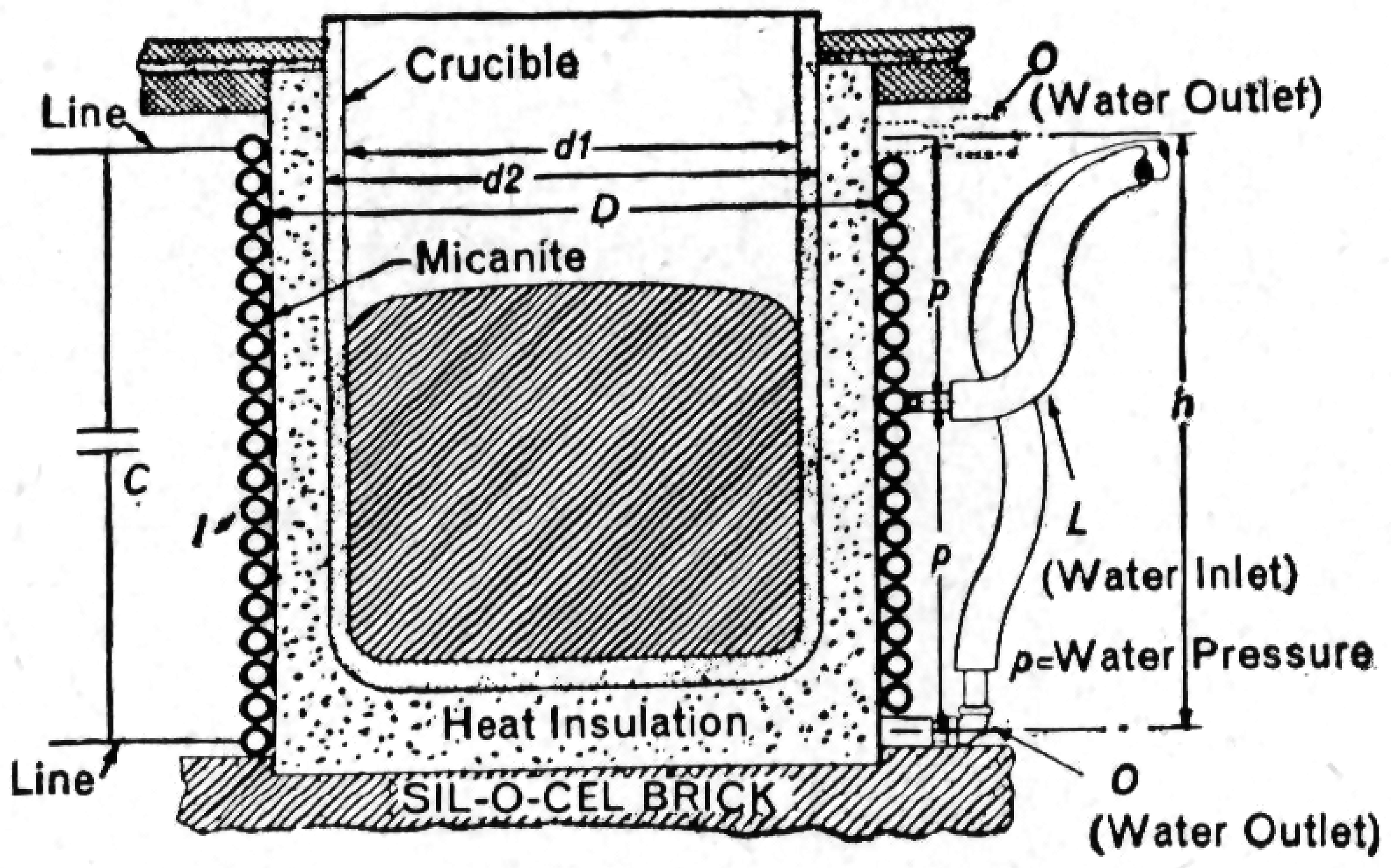

Fig. 7–7. Cross-section of high-frequency electric induction furnace.

The principal characteristics of the induction furnace are: (1) its efficiency increases directly as the capacity (present maximum capacity is 4 tons), (2) the temperature attainable is limited only by the thermal resistance of the metals, (3) melting periods are easily adjustable, (4) practically no metallic losses occur through oxidation, (5) it permits melting without picking up carbon, (6) very rapid melting is possible, (7) it is practically quiet.

7–8. Ingots. When the desired condition of the steel is obtained, the furnace is tapped and the metal is run into a large ladle. Carried by an overhead crane, the ladle is brought over a number of molds, into which the metal is *teemed* through the bottom, as shown in Fig. 7–8A, to produce *ingots*.

These molds are made of cast-iron and are of a wide variety of shapes and sizes, determined largely by the plant practice and by the quantity and the quality or type of steel being produced. Prior to teeming, the molds are thoroughly cleaned and heated to about 300F, and the inside walls are given a coating of graphite or tar, to prevent the steel from sticking. Fig. 7–8B shows a train of ingot molds being teemed.

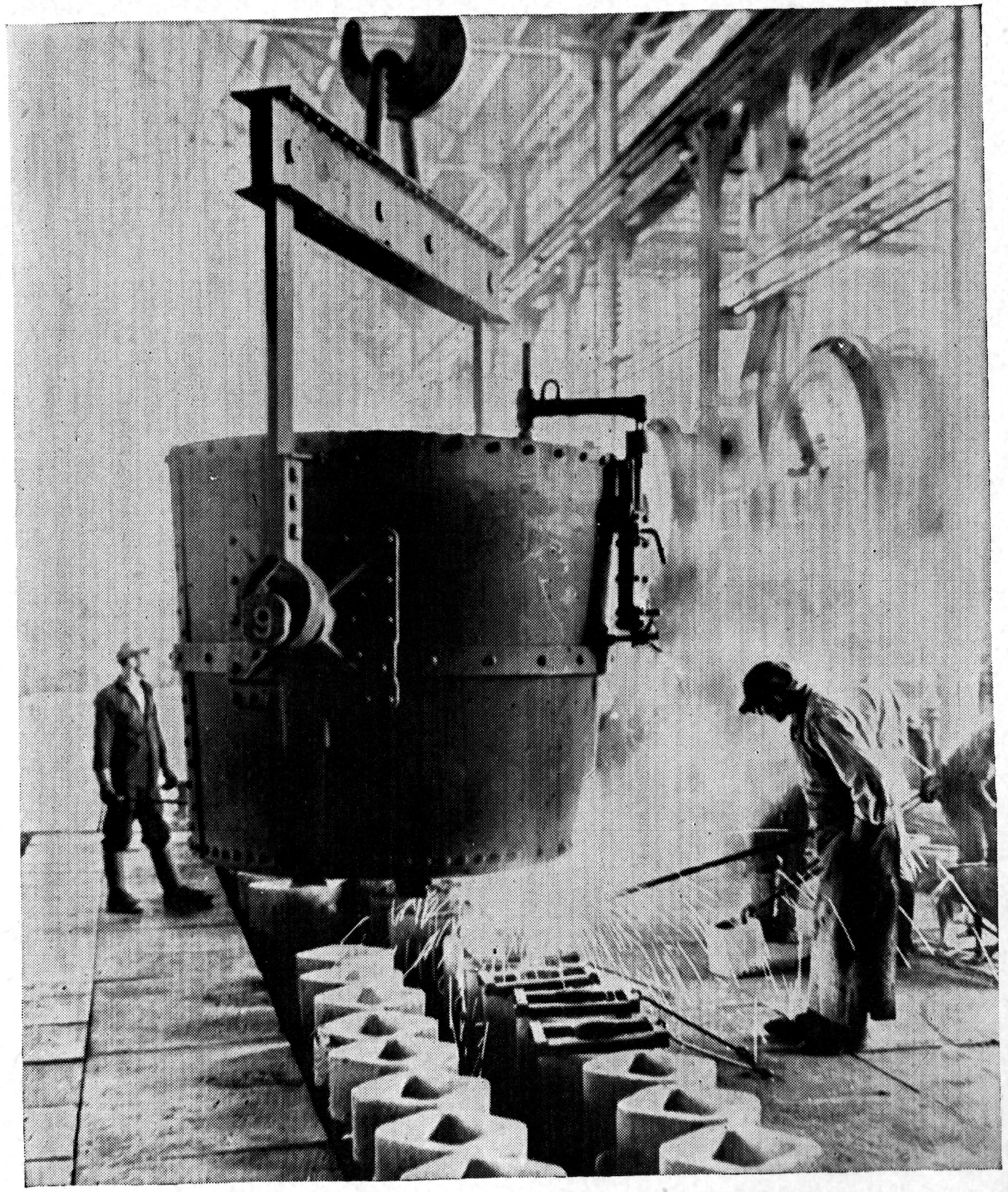

FIG. 7–8A. Teeming of ingots from bottom-poured ladle.

The inside dimensions of molds are larger at one end to provide for the removal of the ingot. The facility by which the mold may be stripped while the ingot remains on the car or *buggy* has favored the practice of standing the mold with the big end down. However, inherent advantages in the production of large ingots and high-quality steels favor setting the molds with the big end up. Except for very large ingots, the bottom of the big-end-up type of mold is closed with a plug of steel or cast-iron,

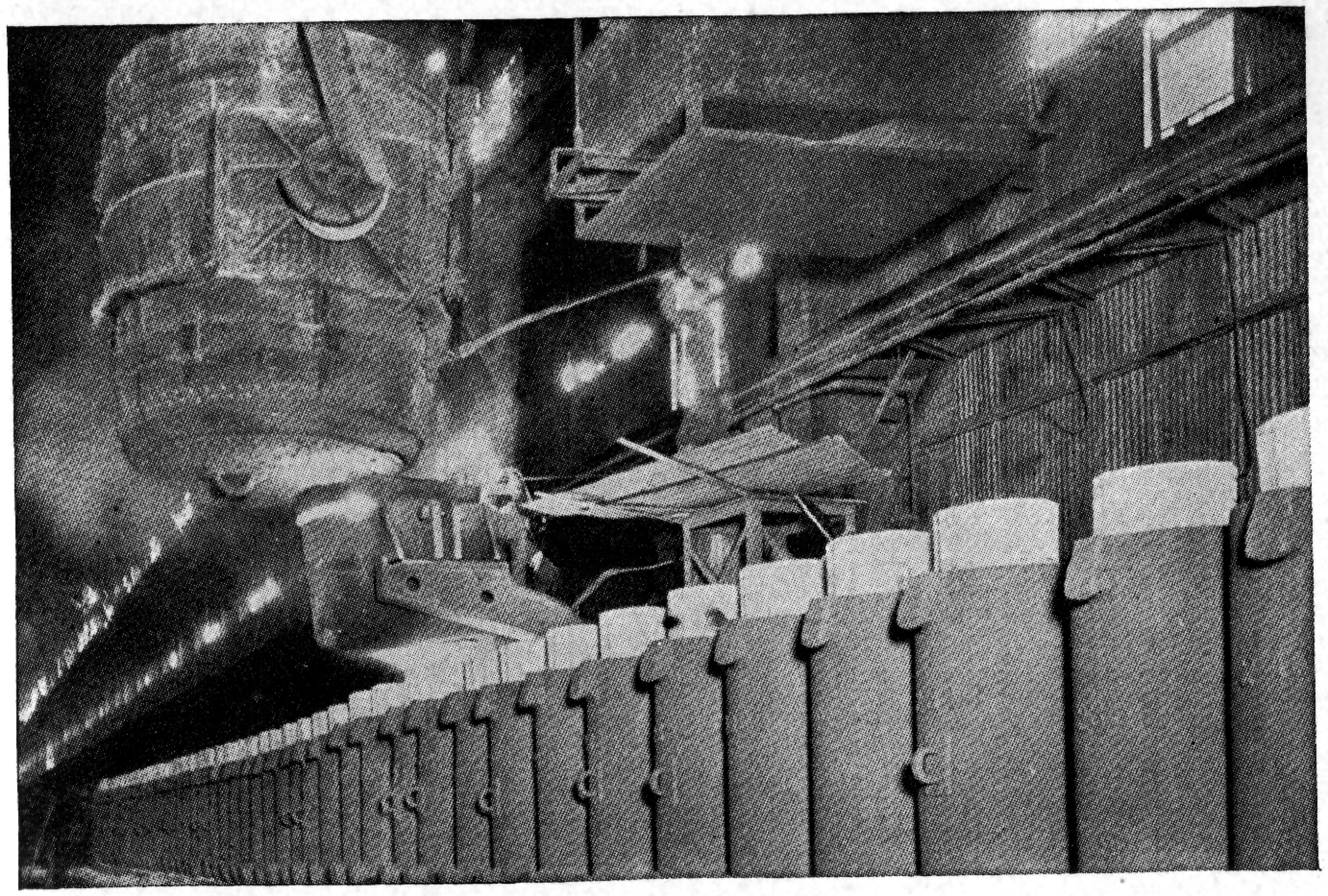

FIG. 7–8B. Teeming a train of hot-top ingot molds. (Courtesy of Gathman Engineering Co.)

inserted to loosen the solidified ingot, as shown in Fig. 7–9. The big-end-down type is open at both ends and rests on a cast-iron or copper *stool* on the buggy.

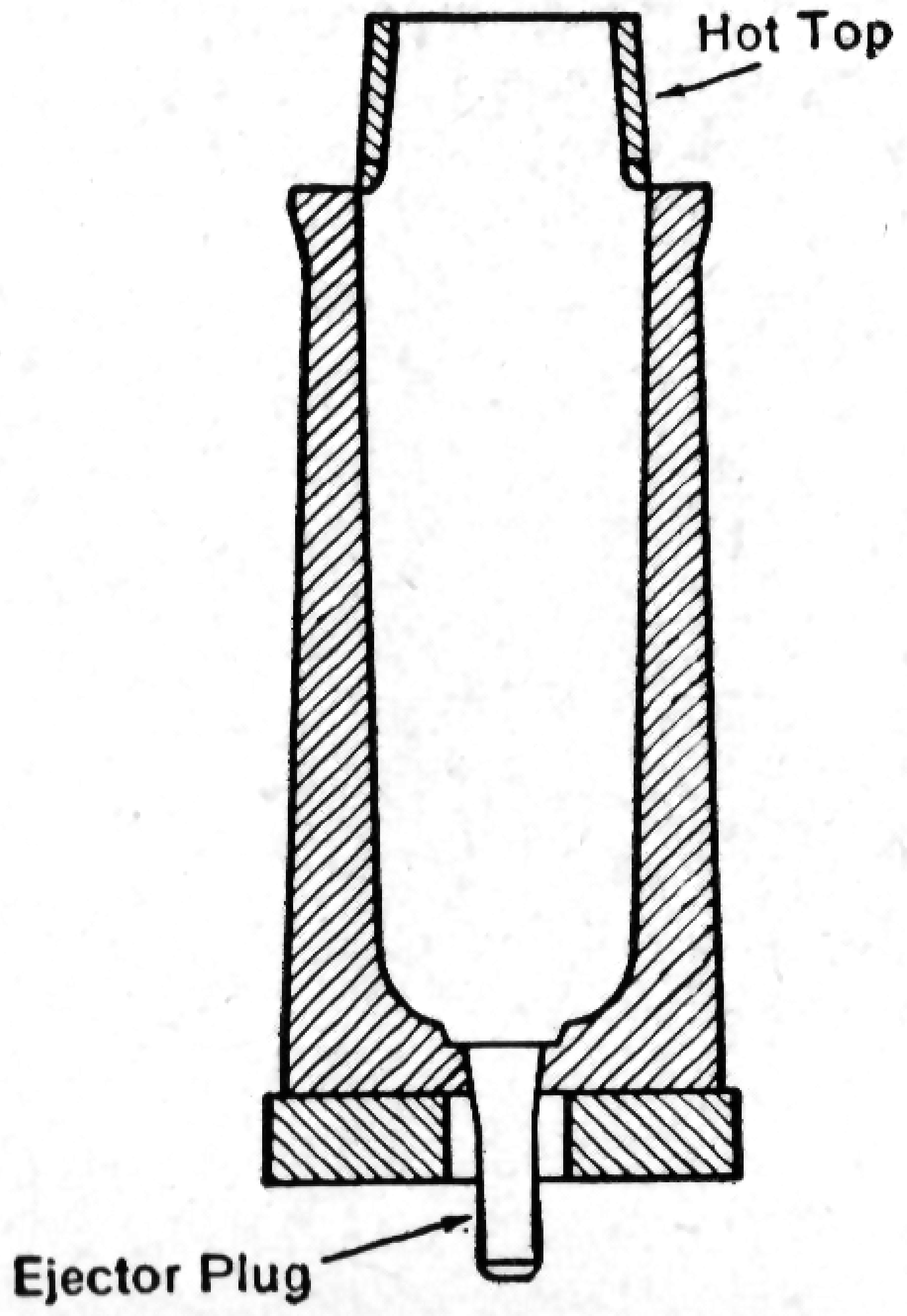

FIG. 7–9. A big-end-up ingot mold with a hot top.

Economics and practical considerations make it advisable to use molds of the smallest size that will serve the desired purpose. For example, tool steels are seldom cast into ingots exceeding 6 in. square and about

40 in. long. Structural steel ingots average 24 in. square and 84 in. long, while ingots for forging and special purposes range from 5 to 9 ft in diameter, are over 16 ft in length, and weigh well over 500,000 lb. Fig. 7–10 shows a forging ingot weighing 554,000 lb.

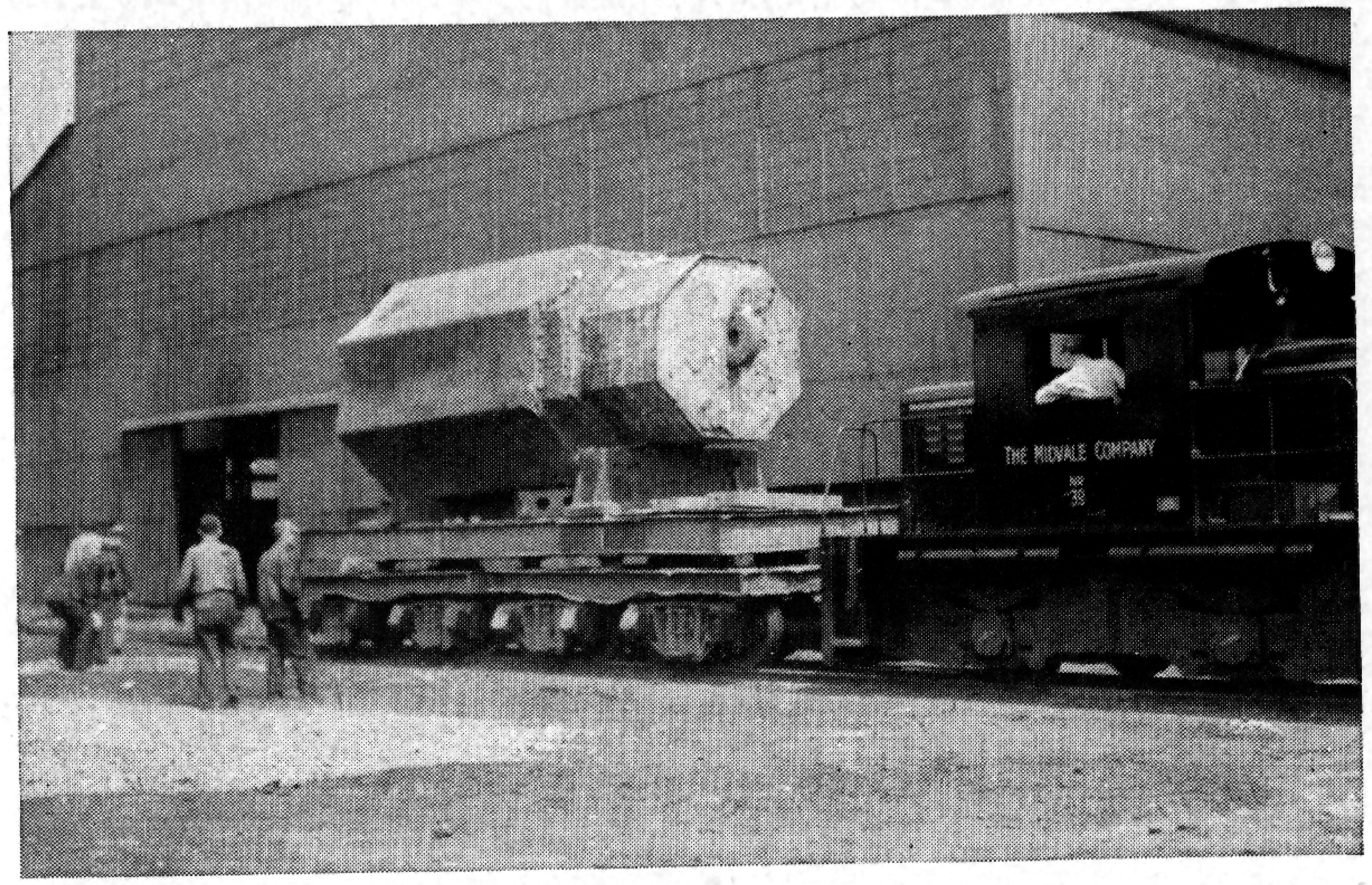

FIG. 7–10. 109-in. alloy steel ingot. Weight 554,000 lb. (Courtesy of The Midvale Company, Philadelphia, Pa.)

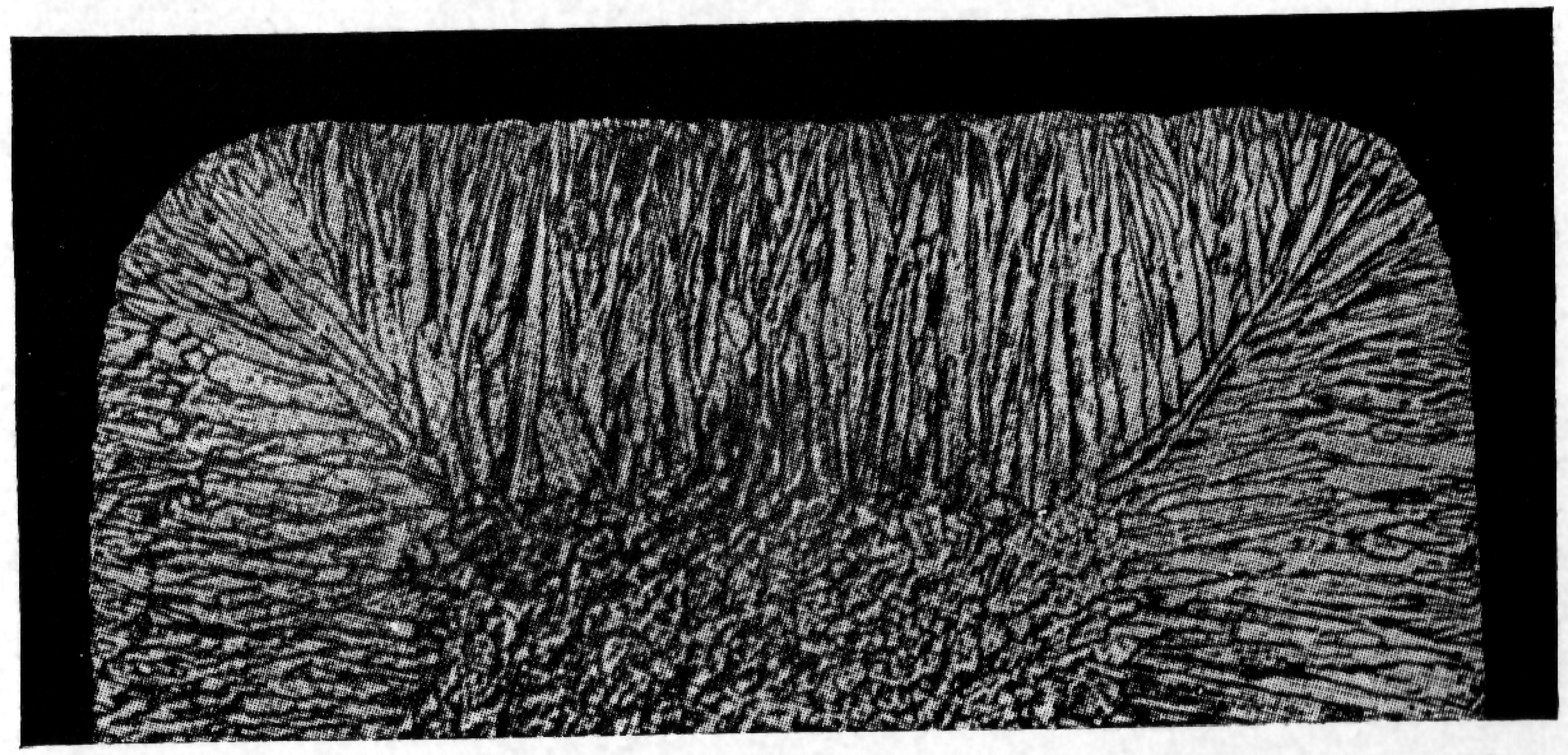

FIG. 7–11. Etched section of big-end-down, fully-deoxidized ingot. Note dendritic structure and diagonal cleavage planes. (Courtesy of Gathman Engineering Co.)

Because grains form simultaneously along planes perpendicular to the mold wall, eventually a junction is effected in a line bisecting the corner angle. In a square or rectangular ingot, these planes form a sharply defined pyramid and constitute the weakest portion of the ingot. Because of the possibility of an ingot rupturing along these planes during hot-rolling or forging, these planes are called *cleavage planes*.

In order to increase surface-to-mass ratio to produce a faster cooling rate, and consequently a more uniform ingot structure, and in order to avoid, as completely as possible, the cleavage planes shown in Fig. 7–11, large molds are corrugated or fluted polygons while rectangular slab molds for plates and sheets, and square molds for structural shapes, are provided with corners with large radii. Cross-sections of ingots are shown in Figs. 7–12, 7–13, and 7–14.

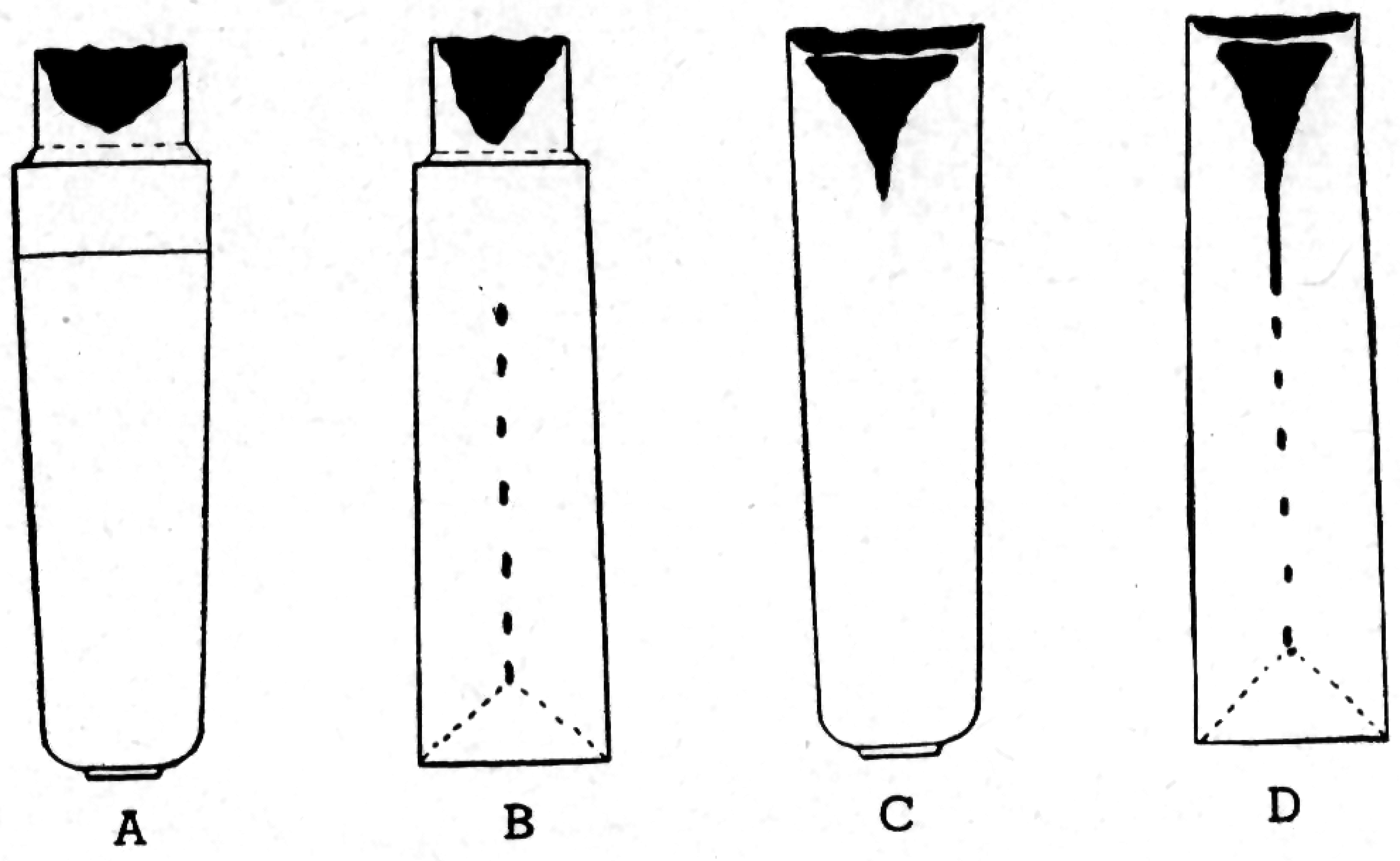

FIG. 7–12. Interior physical condition of big-end-up and big-end-down, fully-deoxidized steel ingots. (Adapted from *The Ingot Phase of Steel Production*, Gathman Engineering Co.)

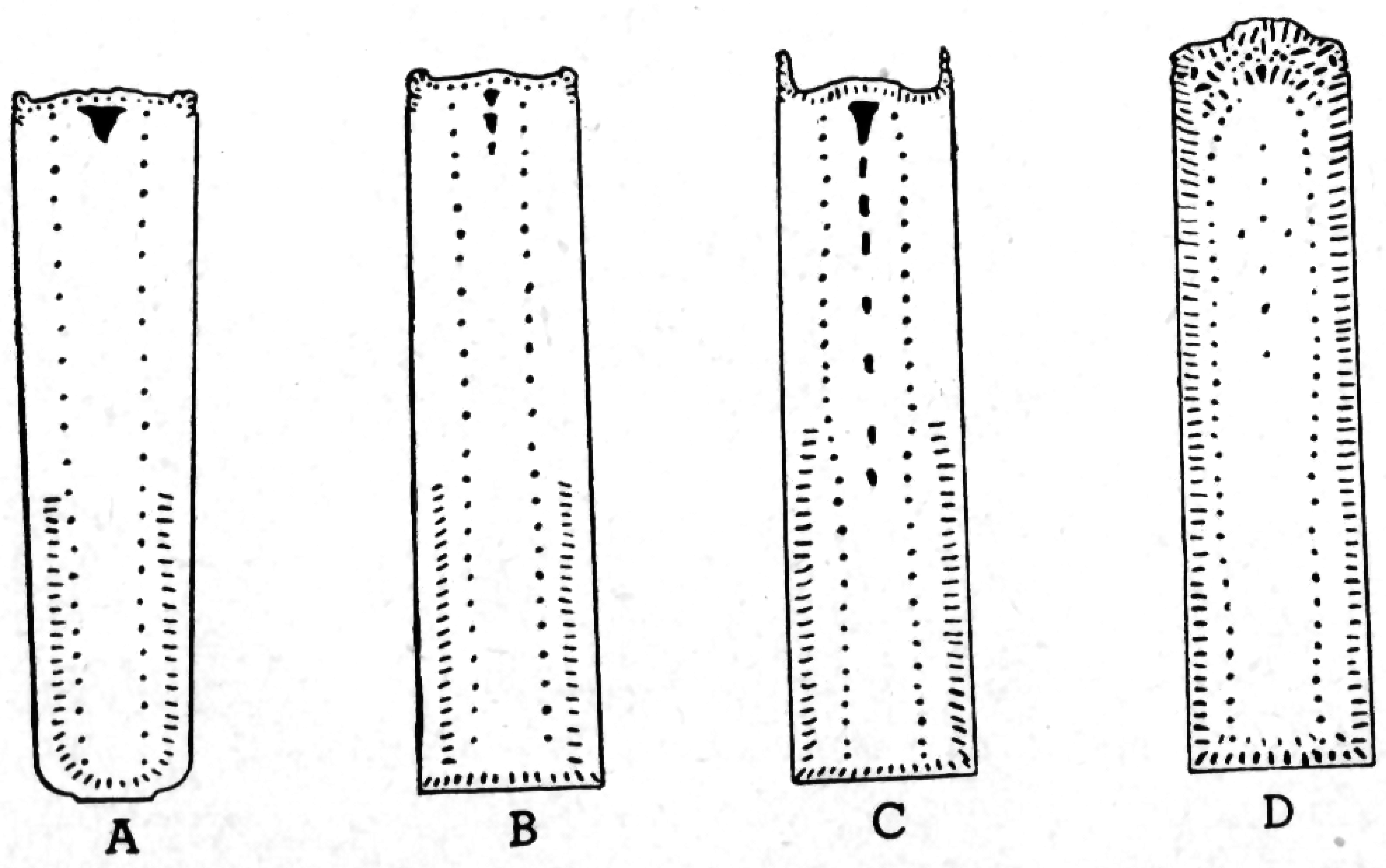

FIG. 7–13. Interior physical condition of big-end-up and big-end-down rimming steel ingots. (Adapted from *The Ingot Phase of Steel Production*, Gathman Engineering Co.)

To minimize shrinkage cavities or *pipe* within the body of the ingot and to facilitate the escape of gases, molds for the production of high-quality steels are often fitted with a formed refractory brick, known as *hot top*, which is placed on top of the mold after being heated to a high temperature. Within these hot tops a reservoir of molten metal is provided to offset shrinkage in volume of the solidifying metal and to retard the freezing of the top of the ingot. The shrinkhead is usually contained within the hot-top area, affording a higher percentage yield of sound metal in the body of the ingot.

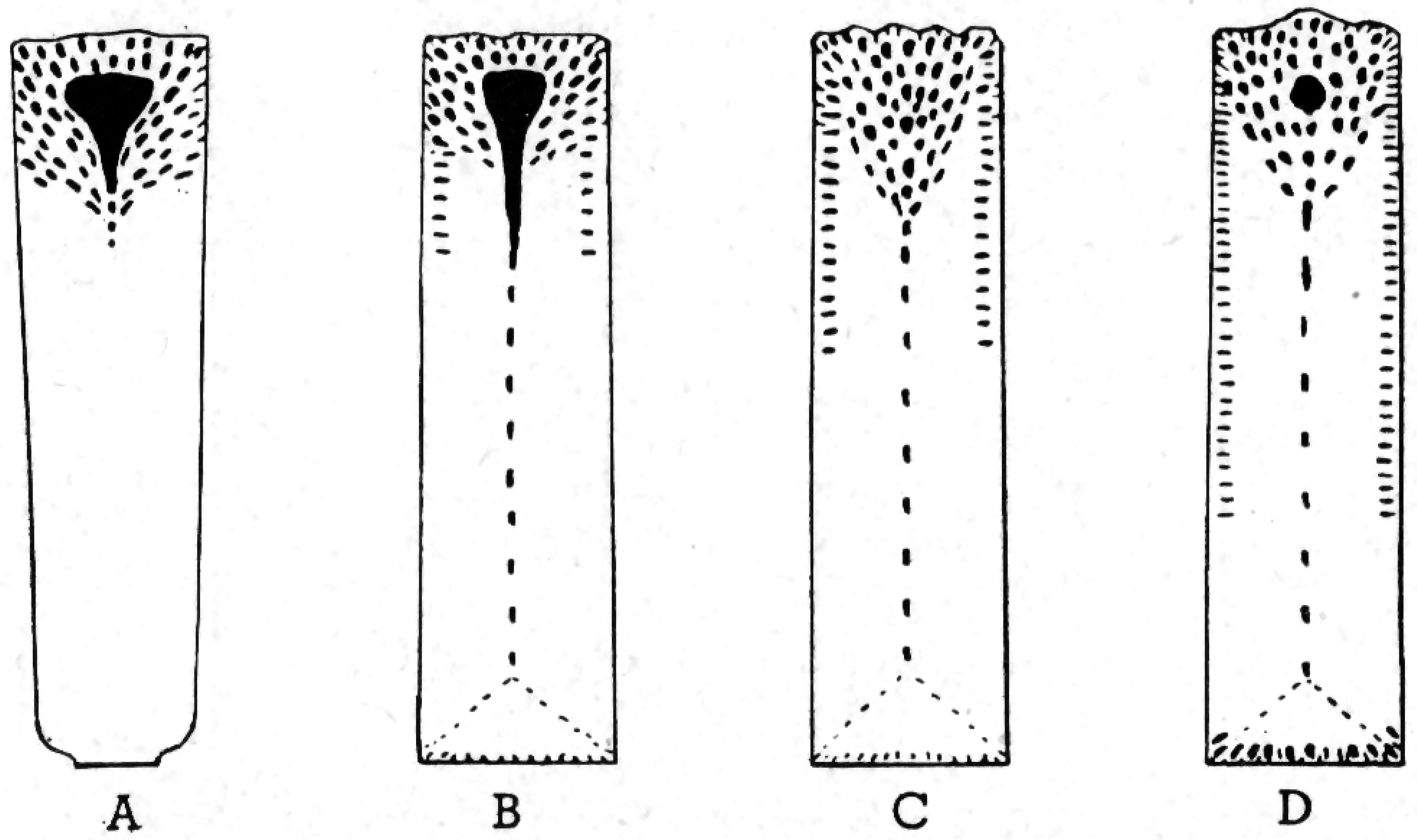

Fig. 7–14. Interior physical condition of big-end-up and big-end-down, semideoxidized steel ingots. (Adapted from *The Ingot Phase of Steel Production,* Gathman Engineering Co.)

Factors which play a more or less important role in the production of high-quality steel after it is tapped from the furnace are (1) size and shape of ingot molds, (2) teeming temperature, (3) sufficient time for complete solidification of the metal before stripping the mold, (4) rate of teeming, (5) provision against splashing of metal against mold walls to cause *scabs,* (6) proper use of mold washes, and (7) degree of deoxidation of the metal.

Improvement in the general physical characteristics of the cast structure by hot-working the metal does not obviate the need for avoiding defects in the ingots, many of which may appear in the finished product.

A detailed description of the mechanics of the solidification of steel is not within the scope of this text; yet, in view of the drastic service demands imposed upon this valuable engineering material, an adequate appreciation of the manufacturing problems by the young engineer user cannot be obtained without some acquaintance with the difficulties encountered and the measures used to meet them.

In the liquid phase, steel is a *homogeneous solution,* consisting of the various constituents comprising the alloy. In the solid state, it becomes a *heterogeneous solid solution,* in which nevertheless the larger proportion of the constituents remain dissolved. When the metal in an ingot mold begins to solidify, the primary crystals formed are predominantly rich in the constituents which have the highest freezing temperature; but, as more heat is dissipated and the temperature of the mass continues to

drop, additional amounts of the melt solidify around crystal nuclei of metal progressively richer in constituents or compounds which freeze at consecutively lower temperatures. This process continues until all of the molten metal has disappeared, the last traces to crystallize consisting principally of the low freezing constituents. In this regard the solidification of molten steel is somewhat analogous to the formation of all solid solutions, such as alloys of gold and silver, copper and tin, lead and tin, aluminum and tin, etc., none of which is a homogeneous entity. This selective freezing process makes possible areas within an ingot in which the analyses may vary widely.

The concentration of the low freezing constituents in certain regions of the ingot is known as segregation; and, if other factors are equal, the degree of segregation is a direct function of the cooling rate of the metal in the crystallizing range of temperature, or within the area bounded by the liquidus and solidus on the diagram in Fig. 9–6.

Segregation to some degree cannot be entirely avoided. However, in fully-deoxidized steels or those steels largely in equilibrium during the cooling period, segregation is negligible. The principal compounds which segregate are those of carbon, sulphur, and phosphorus. Alloying elements do not normally segregate. Since segregation is governed by the duration of the solidifying period, the most highly segregated portion of an ingot is that which is last to freeze. Also, segregation is more pronounced in hot-poured metal and in large ingots.

7–9. Types of Steels. The internal structure of an ingot and the quality of the steel are conditioned principally by the degree of deoxidation or the amount of residual gases—such as hydrogen, nitrogen, or oxides—present in the metal. Large volumes of gases that are soluble in molten metal become insoluble in solid metal; and these gases must be removed from the metal if porosity, or minute gas pockets, are to be avoided throughout the ingot. According to the relative degree of deoxidation, therefore, steels are broadly classified as (1) fully-deoxidized, (2) semideoxidized, and (3) *rimmed,* which may indicate either partial deoxidation or no deoxidation at all.

When steels have been sufficiently deoxidized so that they lie quietly in the mold—indicating no internal gas reaction—they are known as *killed* steels. These are usually uniformly sound, clean, and free from porosity and excessive segregation. Semikilled metal is marked by a brisk evolution of gases during its solidification and is characterized by greater porosity and segregation. The rimmed grades of steel comprise those whose carbon content ranges between 0.05 and 0.15 per cent, with 0.20 to 0.40 per cent manganese; they are known as dead-soft steels. These are only partially deoxidized, usually with manganese. No silicon is used, and analysis reveals but a trace of this element in the steel. Because rimmed steel effervesces violently in the mold, it is referred to as *open* steel. As the metal solidifies, the continual precipitation of the residual gases causes them to sweep upward and inward; this action effects the formation of the rimming which results in the formation of a thick skin of physically sound, clean, ductile metal in contact with the mold wall. The production of this skin, which may vary from a thickness of one to several inches, is a most important requisite for a good rimming steel ingot. When the solidification is complete, a great deal of gas is entrapped, and the interior of the ingot shows considerable porosity, as indicated by Fig. 7–13. Rimmed steel, however, is characterized by an excellent surface which withstands hot-rolling and, because of its high ductility, is well adapted for the severe cold deformation necessary in the production of automobile body sheets and similar parts.

Because the removal of oxides is, under certain conditions, a reversible reaction, complete deoxidation of the metal while in the furnace is difficult, since the oxides tend to diffuse back into the metal from the slag. But, while most of the deoxidation takes place in the furnace, additional deoxidizing materials are added in the ladle and sometimes in the mold also. The most common deoxidizing agent for killed steels is ferromanganese (72 to 82 per cent Mn; 0.7 to 1 per cent Si; 6 to 8 per cent C; 15 to 19 per cent Fe), which is usually added in the furnace, with further additions of ferrosilicon (47 to 52 per cent Si; 48 per cent Fe; 0.55 per cent C) and aluminum made to the ladle or mold. All high-grade plain carbon and alloy tool steels are fully deoxidized. Forging steels whose carbon content exceeds 0.30 per cent are either fully or partly deoxidized. Steels for structural purposes (I-beams, channels, angles, etc.), which range in carbon from 0.15 to 0.30 per cent, are usually only semikilled.

After a lapse of time sufficient for the ingot to solidify, it is removed from the mold and placed in a furnace called a *soaking pit*. Here it remains for several hours or days, depending on its size, until it has uniformly attained the correct working temperature. Ingots shipped away from the plant are allowed to cool slowly to normal temperatures.

QUESTIONS AND PROBLEMS

1. Define steel—plain and alloyed.
2. Give the analysis of a medium-carbon unalloyed steel.
3. Define the term "dead-soft."
4. Name three types of steels, based on the extent to which oxides have been intentionally controlled.
5. Explain the essential factors in the production of steel.
6. Discuss the "big-end-up" and "big-end-down" practice of teeming ingots, from the standpoint of segregation, pipe, cooling rate, and relative percentage of high quality steel per ton of ingot.

7. What are the advantages of multi-sided molds over square molds?
8. Discuss fully the acid and basic processes of producing steel.
9. Rank the steel-making processes as to yearly tonnage and quality of product.
10. Select a steel as to method of producing, analysis, degree of deoxidation and cost for the following parts: transmission gear, aircraft engine crankshaft, steam pipe, track chisel, line shaft for a machine shop, wire for a suspension bridge, railroad rails, automobile connecting rod.
11. What is rimmed steel used for?
12. In what essential respects are the Bessemer, open-hearth and electric-arc processes similar?
13. Show, by means of equations, the functions of Si, C, and Mn when used as recarburizers.
14. What are the objectives to be attained in the duplex process of making steel? Give examples.
15. What constitutes a charge for a Bessemer converter?
16. Sketch the open-hearth furnace and describe the functions of the regenerative chambers.
17. What elements are used as deoxidizers?
18. What are the advantages of the electric-arc process over the open-hearth process?
19. Explain the principle and operation of the induction furnace.
20. What are the functions of hot tops?
21. Discuss step by step the freezing of molten steel in an ingot mold.

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CHAPTER 8

NONFERROUS METALS AND ALLOYS

8–1. Introduction. In both the commercially pure and alloyed form, the nonferrous metals are as indispensable to the proper functioning of industry as are those metals which constitute the ferrous group.

Their many unique characteristics make them peculiarly adapted to uses for which the ferrous metals are unsatisfactory. Some of these characteristics are: generally higher resistance to corrosion, oxidation, or discoloration; luster and pleasing colors, fitting them for decorative purposes; and a high degree of malleability and ductility, facilitating their shaping and fabricating in either the cold or heated condition. Metals like copper, silver, and aluminum are characterized by a high electrical conductivity, while others, such as some of the nickel alloys, are valuable because of their high electrical resistance. Magnesium is known for, and used primarily because of, its lightness in weight, weighing less than one-fourth as much as steel; lead, on the other hand, is heavy and weighs 50 per cent more than steel. Nonferrous metals also differ widely in other specific properties, such as heat conductivity, thermal coefficients, etc.

Some of the strong heat-treated aluminum and magnesium alloys develop strengths comparable to those of structural steels. Nonferrous metals cost more, and their metallurgy is more complex and difficult than that of ferrous metals; however, their characteristic properties, which make them applicable to many industrial uses, justify both the additional cost and the processes for their production.

The principal nonferrous metals used in the commercially pure or alloyed state are copper, aluminum, zinc, magnesium, tin, and lead. To these should be added such other metals as chromium, manganese, cobalt, nickel, molybdenum, titanium, columbium, vanadium, and tungsten; these particular metals are only seldom used in a pure state but constitute an important group of elements, to which may be ascribed the wide range of mechanical and physical properties of both the ferrous and nonferrous alloys, as described later.

8–2. Copper. With the exception of iron, copper is the most important of the commercial metals; but, unlike iron, the major proportion of copper is used in the unalloyed form. Since it has, after silver, the highest electrical conductivity of any metal, the vast electrical industry in its many phases is dependent upon it for wire, bus-bars, dynamos, electric motors, generators, etc. Fully 40 per cent of the commercially pure copper is consumed by that industry; the remainder is used as tubing in ships, refrigerators, and buildings, for pipe fittings, and for automobile and radio parts. In the alloyed form, copper constitutes the principal element in a large number of brasses and bronzes. It is also a minor constituent of many other alloys, as will be pointed out later. In this form its strength, hardness, machinability, and castability are greatly improved; but its corrosion resistance and electrical and thermal conductivity are correspondingly impaired.

Scientific research has provided evidence refuting the popular theory that pure copper once was hardened by a secret process. The so-called "lost art" never existed. The hardness of copper is increased only by cold-working or by alloying with other metals.

Although it is at times found in its pure native state, copper is obtained from two important ores, called *chalcopyrite* ($CuFeS_2$) and *chalcocite* (Cu_2S). In addition to copper, these ores contain iron, sulphur, small amounts of gold and silver, and vast quantities of worthless gangue that consists of silica, alumina, lime, and numerous combinations of other constituents. The average copper content of the ores found in the United States runs between 1 and 2 per cent. Reclaimed and remelted old scrap copper, brasses, and bronzes furnish by far the larger amount of copper consumed yearly.

The metallurgical processes concerned with the production of copper and other nonferrous metals are more complicated, involved, and numerous than those by which iron and steel are produced. For complete descriptions a metallurgical text should be consulted, since such processes may be discussed only inadequately here.

In order that they may be profitably smelted, the copper ores are first concentrated by *ore dressing*, such as grinding and flotation, to separate the undesirable constituents of the gangue from the copper before the actual metallurgical reduction of the metal begins. By this process the concentration is increased to between 20 and 30 per cent. The copper consists of copper sulphide and iron sulphide and contains gold and silver. The concentrates are then charged into a blast furnace, or more commonly a reverberatory furnace, where they are reduced to metallic copper. (A blast furnace for the smelting of copper ores is unlike the iron blast furnace, in that it is rectangular instead of circular and has a width of about 42 in. with a working height of 10 to 14 ft. Its length varies from 10 to 100 ft, according to capacity. The only similarity is that coke is the fuel in each.) The air blast is never heated before entering the copper furnaces, and the charging is done from cars which run along both sides and dump the ore into it directly. Both molten copper and slag run out of the furnace simultaneously and continuously into a settler or reservoir, in which the copper collects and the slag overflows.

The reverberatory furnace for copper smelting shown in Fig. 8-1 is similar in fundamental design to that described in Chapter 6 and shown in Fig. 6-4. These furnaces have a capacity of about 1,400 tons of copper each 24 hr. Their product, which is called *matte*, consists of a mixture of copper and iron sulphides.

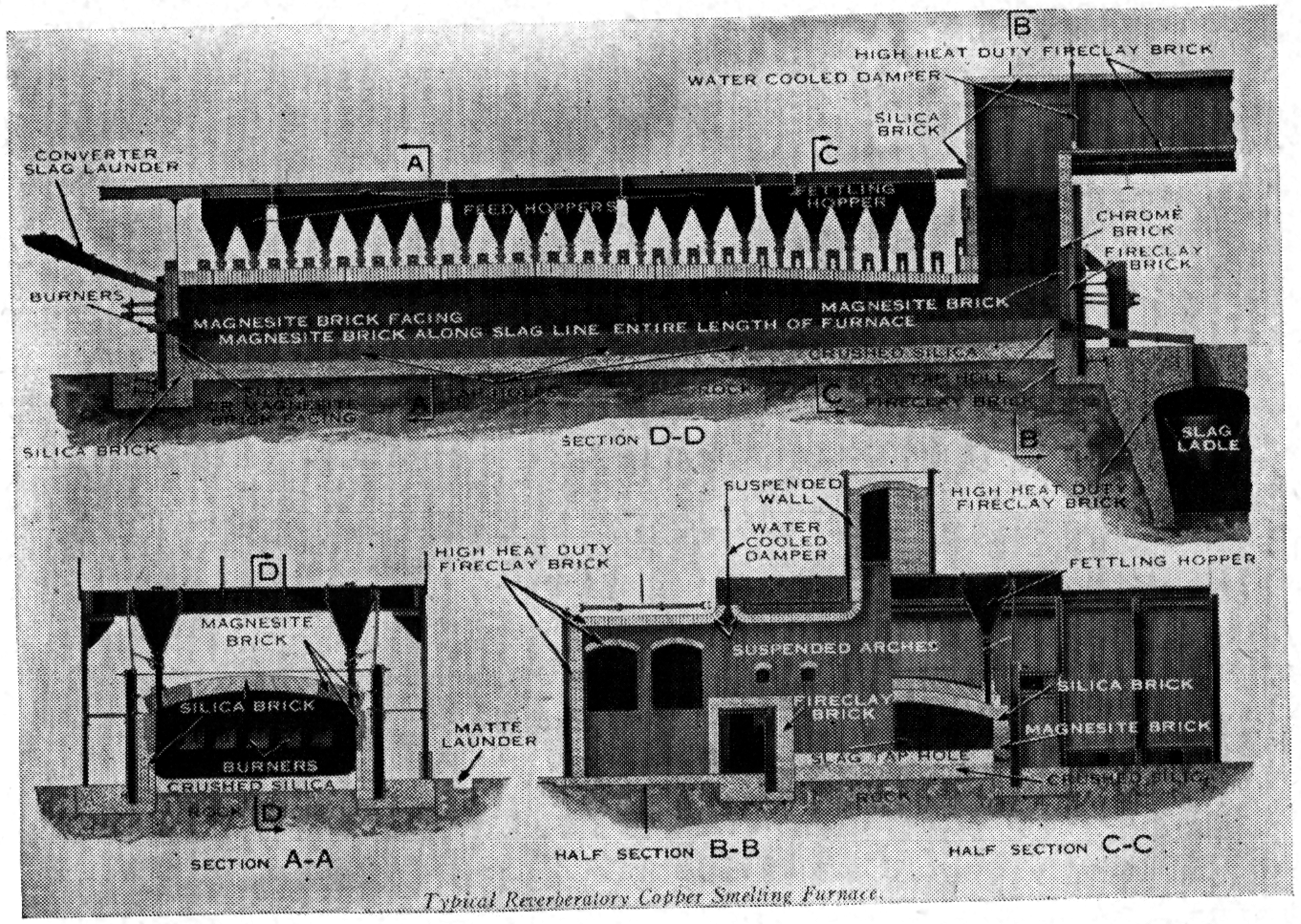
B
HIGH HEAT DUTY FIRECLAY BRICK
WATER COOLED DAMPER
SILICA BRICK
CONVERTER SLAG LAUNDER
A
C
FEED HOPPERS
FETTLING HOPPER
CHROME BRICK
FIRECLAY BRICK
BURNERS
MAGNESITE BRICK
MAGNESITE BRICK FACING
MAGNESITE BRICK ALONG SLAG LINE ENTIRE LENGTH OF FURNACE
CRUSHED SILICA
SILICA OR MAGNESITE BRICK FACING
TAP HOLES
ROCK
SLAG TAP HOLE
FIRECLAY BRICK
SILICA BRICK
SECTION D-D
SLAG LADLE
SUSPENDED WALL
WATER COOLED DAMPER
HIGH HEAT DUTY FIRECLAY BRICK
D
MAGNESITE BRICK
HIGH HEAT DUTY FIRECLAY BRICK
FETTLING HOPPER
SUSPENDED ARCHES
SILICA BRICK
FIRECLAY BRICK
MATTE LAUNDER
MAGNESITE BRICK
BURNERS
SLAG TAP HOLE
CRUSHED SILICA
ROCK
CRUSHED SILICA
ROCK
SECTION A-A
HALF SECTION B-B
HALF SECTION C-C
Typical Reverberatory Copper Smelting Furnace.

FIG. 8-1. Reverberatory copper smelting furnace. (Courtesy of Harbison-Walker Refractories Company, Pittsburgh, Pa.)

From the reverberatory furnace, the molten matte is charged directly into a converter, similar to the Bessemer, through which air is blown to oxidize the iron to ferrous oxide (FeO) and the sulphur to sulphur dioxide (SO_2).

Because SO_2 is insoluble in solid copper and so escapes as the metal solidifies, blisters and a rough surface characterize the product at this stage. It is, therefore, called *blister* copper.

When nearly all the sulphur has been removed, the molten copper is cast into pigs or conveyed in ladles to small reverberatory furnaces for further refining. The presence of small amounts of sulphur, iron, nickel, arsenic, lead, gold, and silver makes blister copper unsuitable for many industrial uses.

For the removal of oxygen existing as cuprous oxide (Cu_2O), with which the copper is somewhat saturated, an interesting operation, known as *poling,* is performed. This consists of inserting green tree trunks (with a diameter of about 10 in. and a length of from 15 to 25 ft) below the surface of the molten copper, where they are slowly charred and consumed, thereby releasing carbon which reduces the oxygen; these elements pass out of the furnace as CO or CO_2. By this means the oxygen is reduced to between 0.03 and 0.05 per cent or 0.27 to 0.44 per cent Cu_2O. After poling, the copper is known as *tough pitch;* and, if the amount of gold and silver is sufficient to warrant the cost of its recovery, it is cast into anodes for electrolytic refining. Otherwise, it is cast into ingots or slabs and rolled into various shapes for industrial applications.

For the recovery of the precious metals the anodes are suspended alternately with copper cathodes in a lead-lined tank containing an electrolyte. The anodes dissolve and deposit on the cathodes, while the gold, silver, and other impurities settle to the bottom of the tank as *slimes.* The cathodes are later fire-refined, while strong reducing agents —such as phosphorus, silicon, cadmium, boron, calcium, or lithium— are added to produce completely deoxidized copper. Other methods have also been utilized in recent years to produce oxygen-free, high-conductivity copper, known as OFHC, which has better physical properties than deoxidized copper although its electrical conductivity is not materially improved. It has a purity of 99.98 per cent.

In the hot-rolled condition, the tensile strength of copper varies from 17,000 to 25,000 psi, with elongation and reduction of area of from 10 to 55 per cent and 8 to 80 per cent, respectively. By rolling or drawing below the recrystallization temperature (400F to 500F), the copper's strength and hardness may be increased over 100 per cent, with a consequent proportional reduction in ductility.

Copper can be fusion- or resistance-welded, brazed or bronze-welded, and soldered. It cannot be flame-cut with the oxyacetylene torch. Because of a reaction between the oxygen in Cu_2O and hydrogen at temperatures above 750F ($Cu_2O + H_2 \rightarrow Cu + H_2O$), oxyacetylene or oxyhydrogen welding should be applied to deoxidized or the oxygen-free copper only. The hydrogen diffuses into the copper faster than the water vapor can escape, and produces high internal stresses, resulting in embrittlement and failure at the grain boundaries.

The copper that is a major constituent of brasses and bronzes and a minor constituent in many other alloys has an industrial importance which is scarcely less than the copper in its pure form. Except for conductivity, ductility, and corrosion resistance, other properties—such as strength, hardness, castability, and machinability—are all improved by alloying.

The best known and perhaps the most widely used of the copper-base alloys are the brasses, which consist of copper with from 5 to 40 per cent zinc. These are in common use for a wide variety of applications. As shown by Fig. 8–2, zinc up to 38 per cent is soluble in copper at temperatures below 800F; and alloys of a composition within this solubility range consist of a single phase and are known as *alpha brass.* In this range, the alloys may be cold-worked, and they possess the best ductility as well as strength. With over 38 per cent zinc, the alloys are less ductile and somewhat harder; therefore, they are more difficult to cold-work. These changes are caused by the embrittling effect of another phase, called *beta.* At elevated temperatures, however, these alloys have good working properties.

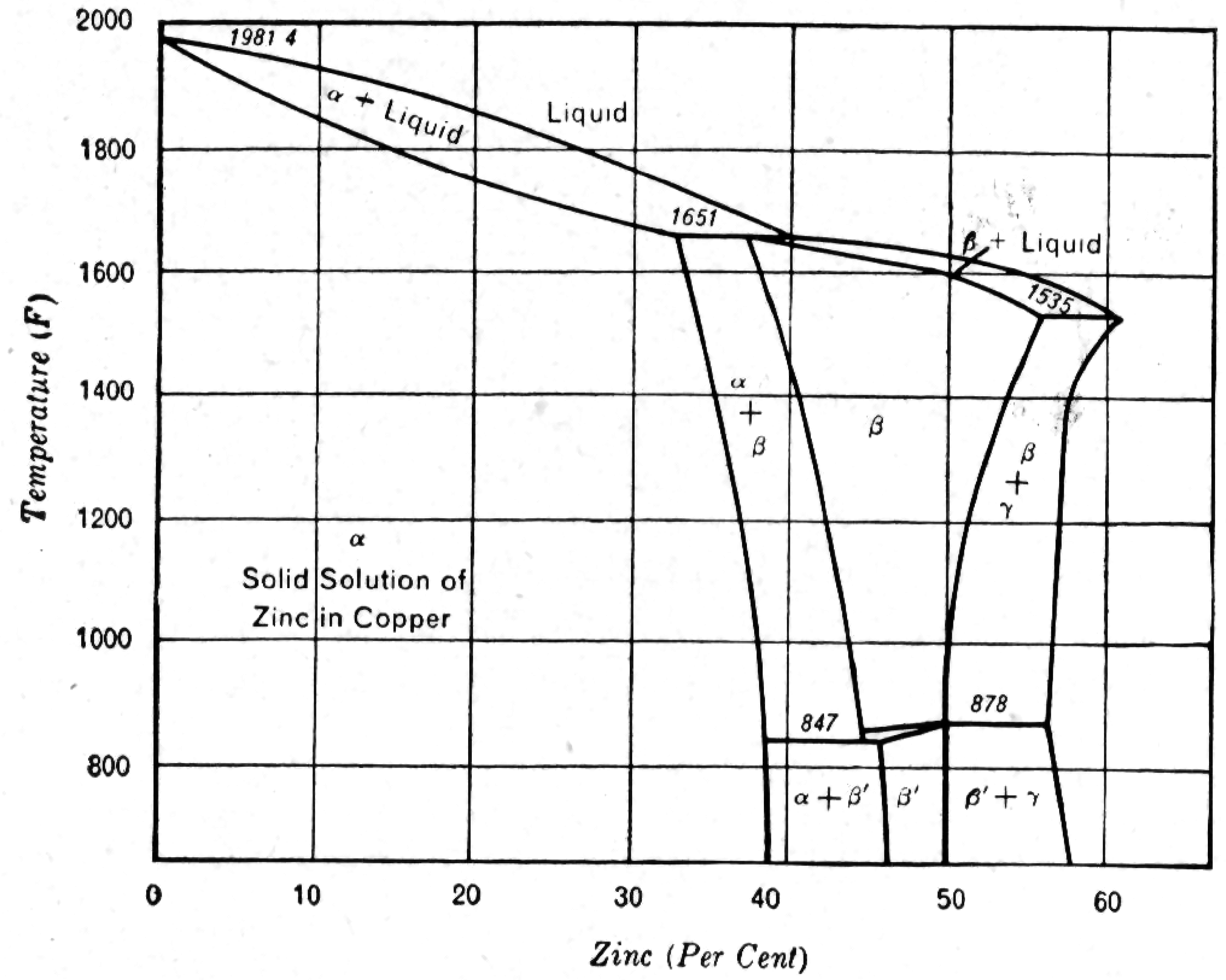

FIG. 8–2. Copper-rich region of copper-zinc constitution diagram. (Adapted from *ASM Metals Handbook,* 1939 ed.)

Copper-zinc alloys are available in both the cast and wrought form. A brief description of alloys of the widest commercial application follows:

8-3. Cartridge Brass. The alloy of copper and zinc known as cartridge brass (see Table 8–1) is one of the most important and most commonly used of the alloys. Its tensile strength varies from about 50,000 psi to over 90,000 psi in the annealed and the spring-tempered (strain-hardened) condition, respectively. Because of its excellent plasticity in the annealed state, it may be subjected to severe cold deformation by cupping, deep drawing, and spinning for cartridge cases, tubes, and musical instruments. Brasses containing from 20 to 36 per cent zinc

TABLE 8–1

NOMINAL COMPOSITIONS OF BRASS*

Name	Composition (Per Cent)				
	Cu	Zn	Pb	Fe	Sn
Commercial bronze	90	10	....	....	....
Red Brass	85	15	0.07 max.	0.07 max.	0.15 max.
Low brass	80	20	....	....	....
Malleable brass	75	25	....	....	....
Admiralty metal	70	29	0.075 max.	0.06 max.	0.90–1.20
Cartridge brass	70	30	0.07 max.	0.05 max.	....
High brass	68	32	0.07 max.	0.04 max.	....
Common high brass	66	34	0.35 max.	0.06 max.	....
Free-cutting brass	61.5	35.5	2.5 –3.75	0.15 max.	....
Brass forging rod	60	38	1.5 –2.5	0.15 max.	....
Muntz metal (tube grade)	60	40	0.30 max.	0.07 max.	....
Naval brass	60	39	0.30 max.	0.10 max.	0.5 –1.0

*Based mainly on ASTM Standards.

have good machinability; and, because zinc costs less than copper, they are less expensive than the low-zinc alloys.

8–4. Muntz Metal. This alloy contains from 39 to 41 per cent zinc and is excellent for such operations as extrusion, stamping, forging, and rolling when carried out at elevated temperatures. It may also be rolled into sheets, drawn into wire, or forged in the cold state. Its machinability rating is fair. It is commonly used for valve stems, architectural work, gas welding rods, and condenser tubes. Its tensile strength varies from 54,000 to 80,000 psi for hot- and cold-finished bars and sheets, with elongations in 2 in. of 45 per cent and 5 per cent, respectively.

TABLE 8–2

TEMPER DESIGNATIONS FOR BRASS SHEETS*

Temper	Reduction in Numbers	Tensile Strength (Psi)	Rockwell B (Samples over 0.040 In. Thick)
¼ hard	1	46,000–56,000	30–60
½ hard	2	53,500–63,500	50–73
¾ hard	3	61,000–71,000	70–80
Hard	4	68,000–78,000	78–85
Extra hard	6	79,000–88,500	85–89
Spring	8	86,000–95,000	88–92
Extra spring	10	89,500–98,500	89–93

*ASTM Standard B36–33.

8–5. Admiralty or Naval Brass. This alloy is similar to cartridge brass except that it contains from 0.90 to 1.25 per cent tin. It has excellent working properties; its machinability is similar to that of mild steel; and it is resistant to most industrial oxidizing conditions. In the hot-rolled state, it has a tensile strength of 50,000 psi, with an elongation in 2 in. of 60 to 75 per cent and a hardness of 10 Rockwell B. By cold-working, its hardness may be increased to 95 Rockwell B and its tensile strength to 90,000 psi, with almost no elongation. It is commonly used for marine parts that will be exposed to sea, air, and steam. Temper designations and the tensile properties of sheet brass are given in Table 8–2.

8–6. Free Machining. These brasses, in addition to copper and zinc, contain from 1 to 3.50 per cent lead with small amounts of iron. Like sulphur in free-cutting steels, these elements slightly reduce the ductility and enhance the machinability. Since chips break off in short lengths, these brasses are used for automatic screw machine products. With a low-lead content, these alloys withstand moderate cold-working and, provided the lead is kept under 2 per cent, they may be hot-forged. They may, however, be hot-rolled if the lead content approaches 4 per cent. The tensile strength varies from 45,000 to 65,000 psi, with elongations in 2 in. from 35 to 15 per cent, respectively.

8–7. Bronzes. In the nomenclature of nonferrous metals, the term "bronze" was originally applied to copper-tin alloys. The term as used today is less explicit and more comprehensive than formerly, since it is applied to many other alloys. For example, an alloy containing 90 per cent copper and 10 per cent zinc is called *commercial bronze.* Welding rod metal of 59 per cent copper, 40 per cent zinc, and 1 per cent tin is also called bronze. Copper-tin-aluminum, copper-tin-manganese, copper-silicon, copper-silicon-manganese, and many other combinations are bronzes in the currently accepted usage of the term.

Next to the brasses, bronzes are the most important of the copper alloys. They have a distinctive yellow color, are generally stronger and harder than brass, may be mechanically worked in the hot or cold state, and have excellent wearing qualities for bearings, bushings, gears, valves, and pipe fittings. Their compositions cover a wide range; and, generally, they are more expensive than copper-zinc alloys.

With a very slow cooling rate from the melt, a maximum of 16 per cent tin is soluble in solid copper, as shown in Fig. 8–3. This proportion, however, is reduced to about 10 per cent with somewhat faster cooling and to about 5 per cent with rapid cooling. In order to avoid the increased hardness and brittleness of the beta phase, most tin bronzes contain about 13 per cent tin and thus assure a single-phase, solid-solution alloy. A common general-purpose bronze contains 90 per cent copper and 10 per cent tin.

Cast gunmetal may contain either 10 per cent tin and 2 per cent zinc or 8 per cent tin and 4 per cent zinc. The remainder is copper. Bell metal has from 15 to 25 per cent tin with from 85 to 75 per cent copper.

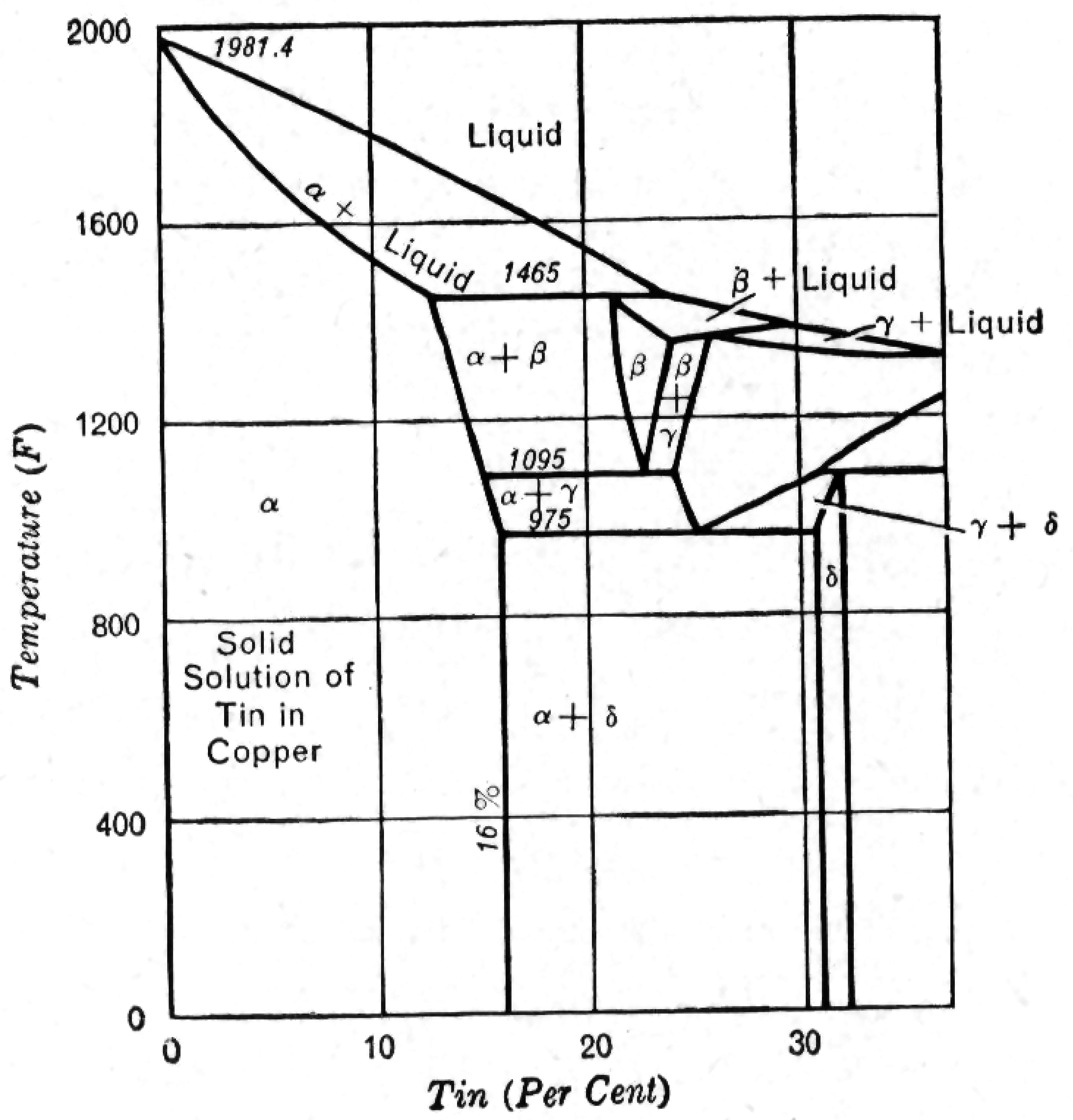

FIG. 8–3. Copper-rich region of copper-tin constitution diagram. (Adapted from *ASM Metals Handbook,* 1937 ed.)

8–8. Manganese Bronze. This alloy consists of from 55 to 71 per cent copper, 38 to 22 per cent zinc, 0.5 to 4 per cent manganese, 0.0 to 1.5 per cent tin, 1.5 to 6 per cent aluminum, 0.4 to 3 per cent iron, and 0.02 to 0.40 per cent lead. The elongation and reduction of area of a separately cast and machined specimen vary from 10 to 40 per cent. This alloy is widely used in the cast condition for parts subjected to corrosive action by sea water, sea air, waste water, and industrial atmospheres. Typical of its application are propeller blades for seagoing vessels, propeller hubs, pump parts, and gears. It is also used to some extent, because of its good wearing qualities, to rebuild worn surfaces and to bronze-weld steel, cast-iron, and malleable cast-iron with the oxyacetylene torch. Its electrical conductivity, varying inversely with the amount of manganese, is 1/4 to 1/5 that of copper. When solidifying from the melt, manganese bronze is characterized by a higher volume shrinkage than that shown by other brasses and bronzes.

8–9. Phosphor Bronze. Like manganese, phosphorus functions both as deoxidizer and as an alloying element. In small amounts, the phosphorus improves the mechanical properties by reducing the Cu_2O. With additional amounts (under 1 per cent) the phosphorus and copper form the hard intermetallic compound Cu_3P, particles of which, when well distributed, render the metal suitable for bearings, gears, and other similar applications where a good wear-resisting surface is required. Phosphor bronze has good cold-working properties and, therefore, may be obtained in several degrees of strain hardness. With adequate cold-working, it is suitable for springs in applications where resistance to oxidation is desirable. Its tensile strength varies from 40,000 psi in the annealed or soft-tempered condition to 110,000 psi in the extra-spring temper condition.

8–10. Aluminum Bronzes. These copper-aluminum alloys, while stronger than the copper-tin bronzes, are comparable in ductility to the copper-zinc brasses. The substitution of aluminum for tin effects a marked increase in their hardness and produces a tensile strength in the hot-rolled condition of up to 80,000 psi with elongation in 2 in. of 45 per cent, while the tensile strength of sheets and wire after cold-rolling or drawing may reach up to 125,000 psi with elongation of 7 per cent.

The maximum solubility of aluminum in solid copper is 9.5 per cent, as shown by Fig. 8–4.

The most desirable combination of properties is obtained with compositions ranging from 4 to 13.5 per cent aluminum, 4.5 per cent iron, and small amounts of nickel, tin, and manganese. Alloys with a maximum of 10.5 per cent aluminum may be mechanically worked either hot or cold, and are characterized by a high resistance to corrosion by sea air and salt

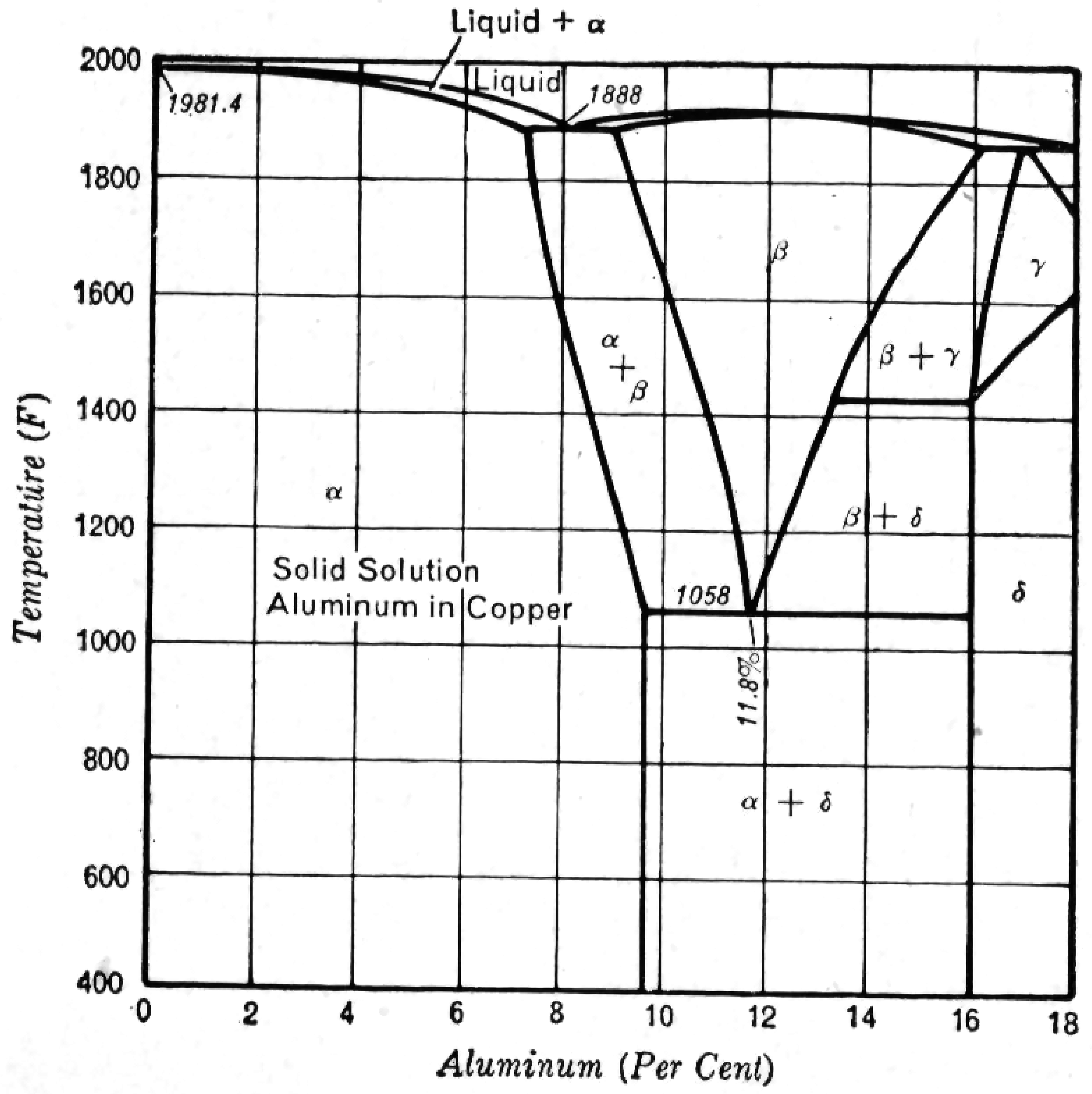

FIG. 8–4. Copper-rich region of copper-aluminum constitution diagram. (Adapted from *Principles of Metallography* by Williams and Homerberg.)

water, and by sulphuric acid and other chemicals. They possess a light yellow color and good wearing qualities; and they retain their hardness well at elevated temperatures. With an aluminum content of about 10 per cent, the alloys may be heat-treated by quenching in water from 1500 to 1600F and reheating between 700 and 1100F, as required.

With over 11 per cent aluminum, the alloys are generally too brittle to withstand working.

The compositions and properties of typical wrought alloys are shown in Table 8–3.

TABLE 8–3

COMPOSITIONS AND PROPERTIES OF SOME WROUGHT COPPER-ALUMINUM ALLOYS

COMPOSITIONS (PER CENT)					PROPERTIES		
Copper	Aluminum	Iron	Nickel	Manganese	Tensile Strength (Psi)	Elongation (Per Cent in 2 In.)	Reduction of Area (Per Cent)
92.00	7.00	1.00	.....	.....	126,100	7.50	34.80
92.00	7.00	1.00	.....	.....	81,200	45.30	61.80
86.49	10.32	3.19	.....	.....	102,900	12.70	17.20
83.00	5.36	3.06	8.58	.....	99,450	27.40	29.40
81.10	9.78	3.74	5.38	.....	104,800	17.30	17.80
83.27	8.64	3.11	.....	4.98	101,150	24.50	32.00
78.66	8.17	3.39	.....	9.78	100,200	26.20	33.40
78.66	8.17	3.39	.....	9.78	118,800	6.30	11.50
87.45	5.62	.....	6.93	.....	109,900	20.00	47.00
87.45	5.62	.....	6.93	.....	117,600	12.00	43.00
87.45	5.62	.....	6.93	.....	65,400	73.00	69.00
87.45	5.62	.....	6.93	.....	96,800	26.00	25.00
84.50	6.36	.....	9.14	.....	105,450	20.80	32.80
92.00	7.00	.....	1.00	.....	124,000	4.50	21.60
92.00	7.00	.....	1.00	.....	66,200	62.30	51.60
92.00	7.00	.....	.....	1.00	112,500	8.50	46.80
92.00	7.00	.....	.....	1.00	66,400	60.80	57.40
88.11	8.91	.....	.....	2.98	89,600	39.00	43.60
82.90	7.15	.....	8.12	1.83	94,450	28.00	39.30

Alloys of the given compositions are available as forgings, rods, sheets, and bars for use as valve stems, diaphragms, condenser bolts; they can be worked by cupping or deep drawing and spinning.

The cast alloys, although similar in composition to the wrought alloys, do not cover so wide a range of proportional combinations. Typical compositions are shown in Table 8–4.

These alloys combine excellent strength with ductility, provide good wear resistance against other metals, and have a high resistance to corrosion, shock, and fatigue. They are used for gears, bearings, pump parts, and similar applications requiring strength and hardness.

8–11. Beryllium Bronzes. The most recent addition to the high-strength copper alloys are those containing from 1 to 2.25 per cent beryllium, with less than 0.50 per cent of either nickel or cadmium added to produce a finer grain structure. These are the hardest of all copper alloys. They are also characterized by a high tensile strength and moderate ductility, and their electrical conductivity and corrosion resistance are similar to those of high purity copper. In wear resistance against steel, they are superior to other bronzes and have better mechanical properties than the aluminum bronzes.

Because of the decreasing solubility of beryllium in copper with decreasing temperatures, these alloys respond to precipitation heat treatment like comparable alloys. The best combination of strength and ductility is obtained after heating to between 1425 and 1475F, quenching in water, and reheating from 480 to 615F for 1 to 4 hr, depending on the properties desired.

TABLE 8–4

TYPICAL COMPOSITIONS OF CAST COPPER-ALUMINUM ALLOYS*

TYPE	COMPOSITIONS (PER CENT)					PROPERTIES		
	Copper	Aluminum	Iron	Tin	Total Other Elements	YP 1,000 Lb	TS 1,000 Lb	EL (Per Cent in 2 In.)
88–9–3...	87 –89.0	7.0– 9.0	2.5–4.0	0.50	1.0	25–30	65–70	20–40
89–10–1..	89.5–90.5	9.5–10.5	1.0 max.	0.20	0.50	50–60	80–90	5–10†
90–9–1...	88.0–92.0	7.0– 9.0	1.25 max.	0.50	1.0	20–25	60–70	20–40
90–10....	88.0–91.0	9.5–10.5	0.20 max.	0.50	1.0	20–25	60–75	15–25

**Metals Handbook* (1939 ed.).
†As heat-treated.

Water quenching from the solution temperature retains the beryllium in a fine state of dispersion, resulting in the high ductility and softness desirable for cold-working, which is commonly done prior to artificial aging to increase the strength of the beryllium bronzes.

With an appropriate amount of cold-working, the strength of beryllium bronzes may be increased from 60,000 psi, with 65 per cent elongation in the annealed state, to 200,000 psi, with 3 per cent elongation. The hardness is also increased correspondingly from 215 to 400 Brinell.

The alloys are marketed in sheets, rods, wire, and tubes. They are used for forming dies, plastic molds, springs, gears, bearings, diaphragms, and welding electrodes and for electrical and aircraft equipment parts.

Because they are hard, nonmagnetic, and incapable of producing sparks, tools made of beryllium-copper alloys are used where fire or explosion hazards prevail. At present, their cost makes their extensive application somewhat prohibitive.

8–12. Copper-Silicon Alloys. A number of copper-silicon bronzes bearing the names Duronze, Everdur, Herculoy, PMG etc., have been made available recently to meet the increasing needs of the chemical and allied industrial processes. In addition to high tensile strength, these alloys possess corrosion resistance to marine and industrial atmospheres, to sulphuric and hydrochloric acids and their salts, to most alkali salts, to alcohol, and to organic acids. They are available as castings and in wrought form as sheets, strip, rods, wire, tubes, and forgings. In the latter form they find application as sewage disposal tanks and equipment, marine hardware, boilers, pump parts, bolts and as water wheels which operate under corrosive conditions.

Silicon is soluble in copper at room temperature to about 4 per cent and slightly higher at elevated temperatures.

Commercial alloys contain from 1 to 4.5 per cent silicon and are, therefore, simple alpha solid solutions. They also contain up to 1.2 per cent manganese, 4 per cent zinc, 2 per cent tin, and 2 per cent iron. Their machinability is improved if from 0.25 to 0.5 per cent lead is added.

These alloys are sufficiently malleable to permit considerable working in the cold or hot state. When properly cold-worked, they attain a tensile strength up to 160,000 psi, compared to about 60,000 psi in the annealed condition. With increasing strength the elongation falls off sharply, varying from 5 per cent (for the cold-worked alloys) to 75 per cent for alloys in the annealed condition. Since they do not respond to precipitation heat treatment, they are dependent on the amount of cold-work to develop the maximum tensile strength.

They may be easily welded by the oxyacetylene, electric-arc, both carbon and metallic electrodes, and resistance processes. Their thermal and electrical conductivity is from 8 to 10 per cent that of copper.

8–13. Nickel-Copper Alloys. Nickel constitutes one of the valuable alloying elements for both ferrous and nonferrous metals. It is soluble in copper in all proportions, and no abrupt and radical change in mechanical properties is evident with changes in composition. In small quantities nickel is not, however, as effective as a similar amount of tin or silicon in increasing the strength of copper. For this reason the nickel content of these alloys ranges from over 5 to 75 per cent. With over 20 per cent nickel the distinctive red color of copper is changed to a silver-gray. It promotes good working and mechanical properties and increases resistance to oxidation and corrosion at elevated temperatures to values like those of the heat-resisting steels.

One of the better known of the nickel-rich copper alloys is designated as Monel metal. This is a natural alloy consisting of between 65 and 70 per cent nickel, 26 to 30 per cent copper, with 5 per cent iron, manganese, and silicon combined. It is primarily a corrosion-resistant metal and is widely used for parts subject to acids, alkalies, brines, food products, and industrial atmospheres. It is silver-gray in color and is commonly used for soda fountains, kitchen tabletops, sinks, laundry tubs, vats for cooking foods, and for such engineering uses as turbine blades, pump rods, and steam valves.

Monel metal is available as sheet, rod, and wire and as castings for many uses.

In the annealed condition, Monel has a tensile strength of about 80,000 psi, with an elongation in 2 in. of 40 per cent. When subjected to cold-drawing or rolling, its strength may reach 100,000 psi, with 25 per cent elongation. Some compositions of Monel known as K-Monel, which contain from 3 to 5 per cent aluminum, respond to precipitation heat treatment, by which their strength is increased to 150,000 psi, with an elongation in 2 in. of 30 per cent. Another modified type known as R-Monel, which consists of 67 per cent nickel, 30 per cent copper, 1.4 per cent iron, and 1 per cent manganese, has improved machinability in the cold-drawn condition and is widely used in parts adapted for screw machine production.

Another series of nickel-copper alloys is known as cupro-nickel, which contains from 20 to 30 per cent nickel, the balance copper with 1 per cent tin. Among many other uses, these are widely used for condenser tubes in ships to resist the action of salt water.

The United States nickel coin is made of 75 per cent copper and 25 per cent nickel.

Nickel-copper alloys may be welded by the gas, electric-arc, or resistance processes. They may also be soft-soldered, bronze-welded, or silver-soldered.

8–14. Aluminum. Aluminum is one of the newest and most important of the commercial metals. A process for its economic production dates back to the decade just preceding the present century. This makes it a definitely modern metal whose application to engineering and household equipment has increased more rapidly than that of any other metal. Its annual consumption is exceeded only by iron, copper, tin, and zinc.

Although the most abundant of all metals in the earth's crust, aluminum is produced commercially from bauxite, a hydrated oxide of aluminum, which conforms to the symbols $Al_2O_33H_2O$ and $Al_2O_3H_2O$. This ore is a mixture of 56 to 59 per cent Al_2O_3, 20 to 28 per cent Fe_2O_3, 3 to 8 per cent SiO_2, 0.5 to 3 per cent TiO_2, and from 10 to 15 per cent H_2O.

The ore is reduced to metallic aluminum by crushing and concentrating, then roasted to oxidize any organic matter, and finally dehydrated to produce a purified Al_2O_3. It is then ground into fine powder and reduced by electrolysis in molten salts of aluminum, sodium, and calcium fluoride in carbon-lined cells or tanks, with carbon electrodes from 8 to 16 in. in diameter serving as anodes. The molten aluminum collects at the carbon lining, which serves as the cathode and is withdrawn periodically at a temperature of about 1800F and cast into ingots. A section of an aluminum reducing cell is shown in Fig. 8–5.

8–15. Characteristics of Aluminum. Commercially pure aluminum has a purity of from 99 to 99.9 per cent; the impurities consist of iron, silicon, and copper. It is obtainable in the wrought form as sheets, rods, wire, extrusions, and forgings and also as castings produced by die-casting, permanent-mold, and sand-mold methods. In its commercially pure form designated 2S, aluminum has a relatively low tensile strength of about 13,000 psi in the annealed state, which may be increased by cold-working to almost 25,000 psi. Since the hardness and strength vary directly with the amount of cold-work, it may be obtained in several degrees of strain hardness, as shown in Table 8–5; other alloys, of which the principal ones are designated 3S and 52S, may also be strain-hardened to develop strengths, as shown.

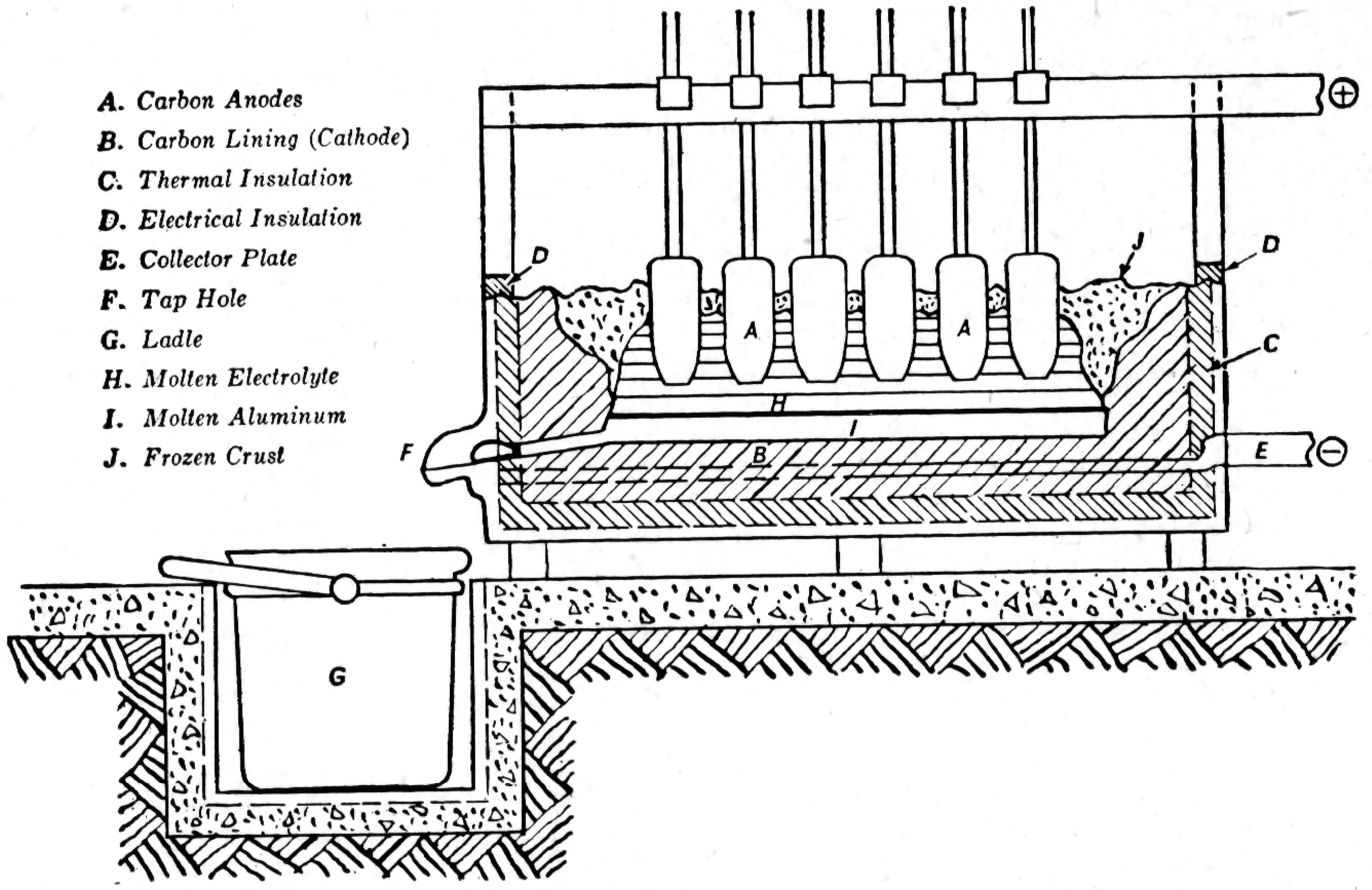

FIG. 8–5. Section of an aluminum reduction cell. (Adopted from *Non-Ferrous Production Metallurgy* by John L. Bray.)

The density of aluminum is 2.75 g/cm^3 (169 lb/ft^3); its melting point is 1214F, and it boils at 3733F. It has a silvery luster, is malleable, has a high thermal conductivity, and has almost 2/3 the conductivity of copper. It also has a high resistance to most corrosive media and may easily be fabricated by resistance and fusion welding, riveting, or brazing. This latter process is widely used for producing oil-, water-, or airtight joints in complicated units in which the joints are inaccessible for welding or riveting. The brazing process is made possible, because the aluminum alloy in sheet, tube, or rod is furnished, for this purpose, with the required amount of aluminum brazing alloy as a clad or coating on the surface. After being assembled with jigs, the unit is immersed in a molten salt bath which serves both as a heating medium and a flux. At a temperature just above its melting point, but below that of the aluminum core, the brazing alloy flows by capillarity between the contacting surfaces to produce strong and tight joints. The unit is subsequently thoroughly cleaned by washing in warm water.

TABLE 8–5

TYPICAL MECHANICAL PROPERTIES OF WROUGHT ALUMINUM ALLOYS IN VARIOUS TEMPERS

ALLOY AND TEMPER*	YIELD POINT (PSI)	TENSILE STRENGTH (PSI)	ELONGATION	
			Sheets (1/16 In. Thick)	Rounds (1/2 In. Diam.)
2S–O, annealed	5,000	13,000	35	45
2S–O, ¼ hard	13,000	15,000	12	25
2S–O, ½ hard	14,000	17,000	9	20
2S–O, ¾ hard	17,000	20,000	6	17
2S–O, hard	21,000	24,000	5	15
3S–O, annealed	6,000	16,000	30	40
3S–O, ¼ hard	15,000	18,000	10	20
3S–O, ½ hard	18,000	21,000	8	16
3S–O, ¾ hard	21,000	25,000	5	14
3S–O, hard	25,000	29,000	4	10
52S–O	14,000	29,000	25	30
52S–O, ¼ hard	26,000	34,000	12	18
52S–O, ½ hard	29,000	37,000	10	14
52S–O, ¾ hard	34,000	39,000	8	10
52S–O, hard	36,000	41,000	7	8

*Designated by Aluminum Company of America.

Because of its many characteristics, aluminum is adaptable for diverse applications which range from collapsible tubes to airplane structural parts, furniture, household appliances, pipe fittings, insulating foil, and light weight freight and passenger railroad cars and buses.

In general the alloys of aluminum have poorer corrosion resistance than the pure metal. Where corrosion resistance as well as high strength are desirable, the base metal may be effectively protected by cladding or bonding with a very thin layer of the pure metal. Since the coating is electrolytically positive to the core metal, it protects edges which may be scratched in handling or which may become exposed in the shearing or forming processes.

Other surface protective measures include plating with zinc, cadmium, chromium, or nickel. The electrolytic formation of a thin oxide coating, by immersion of the metal as an anode in a bath of chromic or sulphuric acid or by dipping in a hot dilute solution of sodium carbonate and potassium dichromate, also furnishes an effective protection as well as an excellent base for paints.

TABLE 8–6

NOMINAL COMPOSITION OF WROUGHT ALUMINUM ALLOYS*

ALLOY	PERCENTAGE OF ALLOYING ELEMENTS; ALUMINUM AND NORMAL IMPURITIES CONSTITUTE REMAINDER								
	Copper	Silicon	Manganese	Magnesium	Zinc	Nickel	Chromium	Lead	Bismuth
2S....	..	..	..	..	..	..	..	..	..
3S....	..	..	1.2	..	..	..	..	..	..
11S....	5.5	..	..	..	..	..	..	0.5	0.5
14S....	4.4	0.8	0.8	0.4	..	..	..	..	..
17S....	4.0	..	0.5	0.5	..	..	..	..	..
A17S....	2.5	..	..	0.3	..	..	..	..	..
18S....	4.0	..	..	0.5	..	2.0	..	..	..
24S....	4.5	..	0.6	1.5	..	..	..	..	..
25S....	4.5	0.8	0.8	..	..	..	..	..	..
32S....	0.9	12.5	..	1.0	..	0.9	..	..	..
A51S....	..	1.0	..	0.6	..	..	0.25	..	..
52S....	..	..	..	2.5	..	..	0.25	..	..
53S....	..	0.7	..	1.3	..	..	0.25	..	..
56S....	..	..	0.1	5.2	..	..	0.1	..	..
61S....	0.25	0.6	..	1.0	..	..	0.25	..	..
70S....	1.0	..	0.7	0.4	10.0	..	..	..	..

*Aluminum Company of America.

TABLE 8–7

NOMINAL COMPOSITION OF ALUMINUM SAND-CASTING ALLOYS*

ALLOY	PERCENTAGE OF ALLOYING ELEMENTS; ALUMINUM AND NORMAL IMPURITIES CONSTITUTE REMAINDER						
	Copper	Iron	Silicon	Zinc	Magnesium	Nickel	Manganese
43.....	..	..	5.0	..	..	..	..
47.....	..	..	12.5	..	..	..	..
108.....	4.0	..	3.0	..	..	..	..
112.....	7.5	1.2	..	2.0	..	..	..
122.....	10.0	1.2	..	..	0.2	..	..
142.....	4.0	..	..	..	1.5	2.0	..
195.....	4.0	..	..	..	..	..	..
212.....	8.0	1.0	1.2	..	..	..	..
214.....	..	..	..	..	3.8	..	..
220.....	..	..	..	..	10.0	..	..
A334.....	3.0	..	4.0	..	0.3	..	..
355.....	1.3	..	5.0	..	0.5	..	..
A355.....	1.4	..	5.0	..	0.5	0.8	0.8
356.....	..	..	7.0	..	0.3	..	..
645.....	2.5	1.2	..	11.0	..	..	..

*Aluminum Company of America.

8–16. Aluminum Alloys. Like other metals the mechanical and physical properties of aluminum are both impaired and improved by alloying with other metals. For instance, the alloys have higher strength and hardness than the pure metal, but somewhat lower ductility and corrosion resistance. They also have a higher specific gravity. Because of the increased strength, aluminum finds its widest industrial application in combination with copper, silicon, magnesium, manganese, zinc, nickel, iron, or chromium. The nominal compositions of some of the more common alloys are given in Tables 8–6, 8–7, 8–8, and 8–9.

TABLE 8–8

NOMINAL COMPOSITION OF ALUMINUM PERMANENT-MOLD CASTING ALLOYS*

ALLOY	PERCENTAGE OF ALLOYING ELEMENTS; ALUMINUM AND NORMAL IMPURITIES CONSTITUTE REMAINDER					
	Copper	Iron	Silicon	Zinc	Magnesium	Nickel
43.....	..	..	5.0	..	..	..
A108.....	4.5	..	5.5	..	..	..
B113.....	7.0	1.2	1.7	..	..	..
C113.....	7.0	1.2	4.0	2.0	..	..
122.....	10.0	1.2	..	..	0.2	..
A132....	0.8	0.8	12.0	..	1.0	2.5
138.....	10.0	1.4	4.0	..	0.2	..
142.....	4.0	..	..	..	1.5	2.0
B195.....	4.5	..	2.5	..	..	..
A214.....	..	..	..	1.8	3.8	..
355.....	1.3	..	5.0	..	0.5	..
356.....	..	..	7.0	..	0.3	..

*Aluminum Company of America.

TABLE 8–9

NOMINAL COMPOSITION OF ALUMINUM DIE-CASTING ALLOYS*

ALLOY	PERCENTAGE OF ALLOYING ELEMENTS; ALUMINUM AND NORMAL IMPURITIES CONSTITUTE REMAINDER				
	Copper	Silicon	Nickel	Magnesium	Iron
13...........	0.6	12	..	..	2.0
43...........	0.6	5	..	..	2.0
81...........	7	3	..	..	..
82...........	14	5	..	..	..
83...........	2	3	..	..	..
85...........	4	5	..	..	2.0
93...........	4	2	4	..	..
218...........	0.2	0.3	..	8	1.8

*Aluminum Company of America.

8–17. Heat Treatment of Aluminum Alloys. Aluminum alloys of suitable composition in both the cast and wrought condition are improved in hardness and tensile strength by a heat treatment known as solution and precipitation. In this treatment, the alloys are heated to a temperature below the melting point but above the *Solvus*, Fig. 8–6, to produce solubility of all constituents. This corresponds in principle to heating steels above their critical temperature to produce an austenite solid solution. After sufficient time to insure uniformity, they are rapidly quenched in water, resulting in a supersaturated solid solution at room temperature. The metal is then relatively soft, has high ductility, low tensile strength, and poor conductivity.

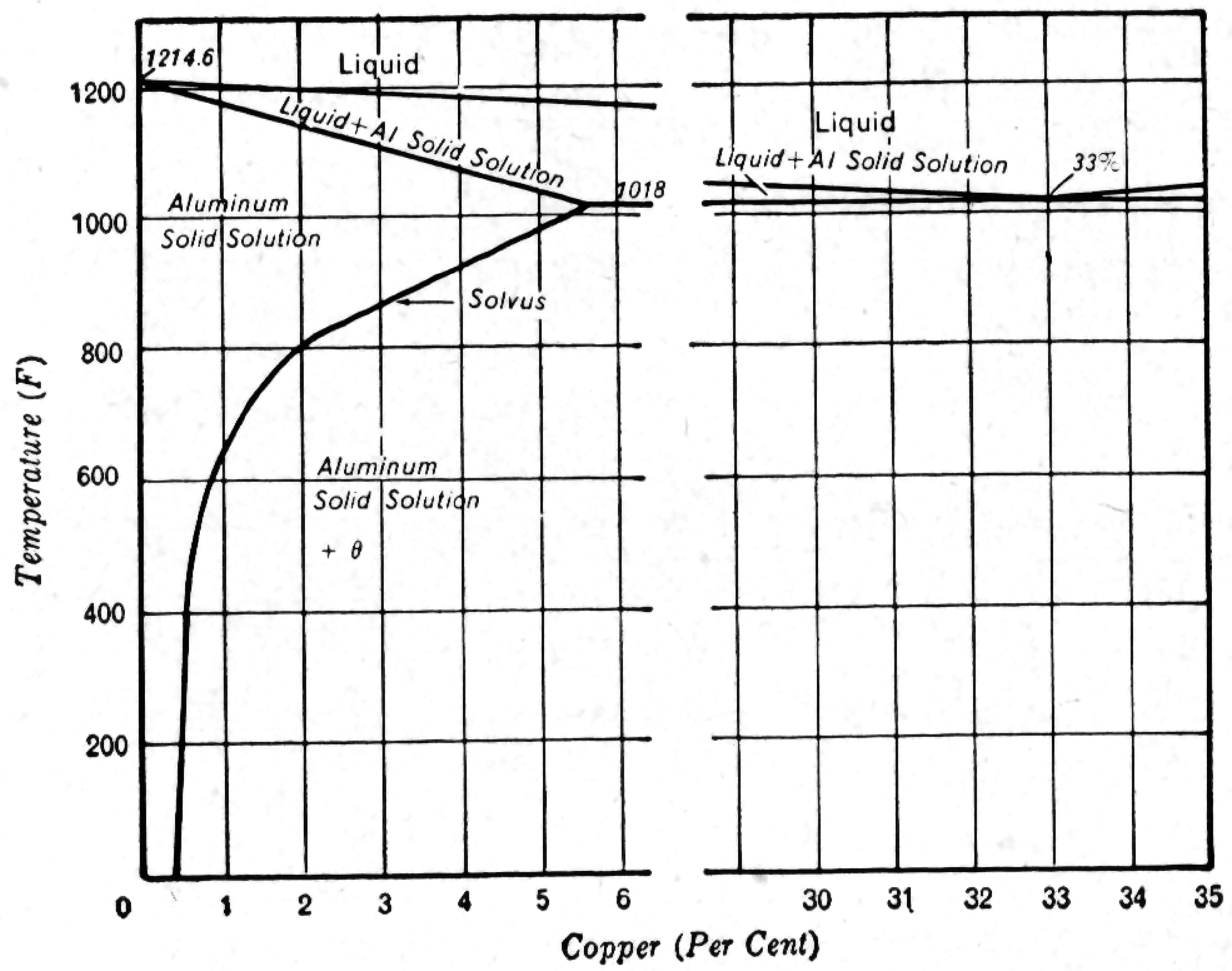

FIG. 8–6. Aluminum-rich region of aluminum-copper constitution diagram. Note decreasing solubility of copper with decreasing temperature. (Adapted from Diagram of Stockdale, Dix, and Richardson.)

The second phase, known as aging or precipitation, is carried out either at ordinary temperatures for some alloys (of which the 17S Duralumin is one of the first and best examples) or by heating to between 315 and 355F for 8 to 18 hr to produce artificial aging. During aging, a remarkable increase in both hardness and strength is realized, which is attributable to the precipitation of some phase from the solid solution, such as $CuAl_2$, Mg_2Si or, depending upon the alloy, some other intermetallic compound. A progressive increase in hardness is noted until a critical dispersion of the constituents is reached. With overaging, the strength and hardness decrease. To inhibit age-hardening and thus retain ductility, parts may be kept in deep freezing containers or in dry ice. For further data on aluminum and its alloys, the student is referred to excellent material furnished by the Aluminum Company of America and other producers of the metals.

8–18. Zinc. The major sources of zinc are the ores, zinc blende (ZnS), zinc carbonates ($ZnCO_3$), and zincite (ZnO). The mineral deposits of zinc-blende ores, however, are much more extensive than the latter two.

Prior to actual smelting, the ores are concentrated by flotation processes, whereby the zinc content is increased from an average of 3 per cent to between 35 and 65 per cent.

While each one requires a somewhat different handling, according to the character of the impurities, the sequence of operations to which zinc is subjected is in general (1) roasting or heating below the melting point in the presence of an oxidizing atmosphere to convert zinc sulphide to zinc oxide and sulphur dioxide, and (2) distillation or reheating the zinc oxide in retorts with a carbonaceous agent such as coke, coal, or charcoal to reduce the oxide and volatilize the zinc which passes off and condenses in liquid form in a heated condenser, from which it is periodically removed and cast into slabs called spelter. This crude zinc, containing iron, lead, cadmium, and arsenic as impurities, is used without further refining for the galvanizing of steel products. By fractional distillation or electrolysis, zinc with a purity of 99.99 per cent is obtained for the purpose of alloying with copper and other metals. In its pure form zinc is of only minor importance as an engineering metal. Its chief value lies in its cheapness, its resistance to corrosion, and its usefulness as a major alloying element in brass and as a minor constituent of aluminum, nickel, silver, tin, manganese, and magnesium alloys.

Besides being an important alloying element, zinc is also extensively used as a base metal in zinc-base die-castings (see Chapter 5), in electroplating and in galvanizing.

Commercially pure zinc in the wrought condition has a tensile strength between 16,000 and 19,000 psi, with elongation in 2 in. of 40 to 70 per cent. Cold-rolled zinc alloy, containing from 0.15 to 1 per cent lead, 0.020 per cent iron, and from 0.10 to 0.36 per cent cadmium, has a tensile strength up to 26,000 psi and an elongation of 30 to 60 per cent.

Zinc is of a bluish gray color, is highly crystalline, and is obtainable as sheets, strip, wire, and rod.

It is slightly lighter than iron, having a density of 7.14. Its melting point is 787F and it boils at 1665F. Its electrical conductivity is approximately 1/3 that of copper.

8–19. Magnesium. Magnesium is the lightest of the metals used commercially. Its specific gravity of 1.74, compared to 2.70 for aluminum and 7.87 for iron, makes it less than 2/3 as heavy as aluminum and less than ¼ as heavy as iron. It melts at 1204F, boils at 2025F and is silvery white in color. Since magnesium hardens rapidly upon cold-working, only a small amount of cold deformation is possible without annealing.

However, magnesium and its alloys may readily be worked at temperatures in the range of 450 to 600F. Extruded shapes, rods, wire, and, frequently, sheets are hot-formed. Its strength is less than that of aluminum, and it is not so good a conductor of electricity as aluminum. Under ordinary dry atmospheric conditions magnesium scarcely corrodes but gradually becomes dull by the formation of a protective film. It is also resistant to many chemicals.

Source. The principal source of magnesium in the United States is a salt brine containing magnesium chloride located in various parts of the country. It is also obtained from the minerals Magnesite ($MgCO_3$) and Dolomite ($(Ca,Mg)CO_3$), which are found in abundance.

Extraction. Magnesium is principally obtained by the evaporation of magnesium chloride solution, from which crystals of an impure magnesium chloride salt, called carnallite, is precipitated. Like aluminum, the salt is next dissolved in a fused bath of mixed fluorides, in which the anodes are graphite and the cathodes are iron. As the metallic magnesium is liberated, it rises to the surface, where it is protected against oxidation and is skimmed off at intervals. The crude metal is later refined to a purity of 99.99 per cent by distillation.

TABLE 8–10

Typical Composition of Magnesium Alloys

Composition (Per Cent)				Characteristic Use
Aluminum	Zinc	Manganese	Magnesium	
6.0	3.0	0.3	Balance	Sand, permanent mold, and pressure die-castings
10.0	None	0.2	Balance	Sand, permanent mold, and pressure die-castings
8.5	0.5	0.2	Balance	Extruded rod, shapes, and press forgings
6.5	0.75	0.3	Balance	Extruded rod, shapes, and press forgings
4.0	None	0.3	Balance	Rolled sheet and plate
None	None	1.5	Balance	Rolled sheet and plate

The minerals are converted into chlorides by first heating to remove the carbon dioxide and then adding water and chlorine gas. The solutions are later dehydrated and the salts fused in an electrolyte.

The principal industrial contribution of magnesium is made in the form of useful alloys, the most popular of which are those containing aluminum and zinc. The compositions and uses of typical magnesium alloys are given in Table 8–10.

Magnesium is also a minor alloying constituent in other metals, especially aluminum in which it usually constitutes 0.20 to 10 per cent.

Magnesium-base alloys in the cast condition have tensile strength between 18,000 and 35,000 psi, with elongations in 2 in. of 3 to 12 per cent. Wrought alloys in rods and sheets have a tensile strength of 38,000 to 48,000 psi, with elongations of from 5 to 16 per cent.

Some of the specific commercial uses of magnesium alloys are in aircraft engine crankcases, landing wheels, oil pumps, packaging equipment, household appliances, foundry flasks, and in many other applications where light weight is desirable.

Magnesium alloys are the easiest of the metals to machine; but precautions must be taken against fire, since the metal may easily be ignited by friction with dull tools or by grinding sparks. Care must also be exercised so that no moisture is present in molding sands, because molten magnesium decomposes water to produce explosive hydrogen.

A comparatively small amount of pure magnesium is used for deoxidizing brass, bronze, and nickel silver.

8-20. Tin. The increase in the annual consumption of tin follows closely the development of the canning, dairy, brewery, plumbing, electrical, paper, and confectionery industries.

The chief sources for the supply of tin are the Straits Settlements, Bolivia, Dutch East Indies, China, Malaya, and Siam. No appreciable tin deposits exist in North America. However, since attention has been devoted to the reclaiming of tin from scrap tin plate, a substantial amount of the tin supply of the United States has come from this source for the past 20 years.

The principal tin ore is the oxide SnO_2, called cassiterite, which contains 78.60 per cent Sn when pure. There are, however, no high-grade ores in existence at present. The Bolivian ores yield from 4 to 8 per cent Sn, with those from other sources yielding considerably less. Tin oxide is associated with the sulphides of iron, arsenic, copper, bismuth, zinc, and lead.

After the ore is concentrated to contain approximately 60 per cent tin by flotation-gravity, it is roasted or heated from 1000 to 1200F to remove arsenic and sulphur and convert the accompanying metals to oxides. Without affecting the tin oxide, the oxides of copper, iron, zinc, and bismuth are removed by leaching with dilute sulphuric acid (H_2SO_4) or hydrochloric acid (HCl). The tin oxide is subsequently smelted in a blast furnace like that used for lead or, more commonly, in a reverberatory furnace. These furnaces are fired with solid fuel and have a hearth approximately 12 by 30 ft, with a capacity of 8 to 12 tons of tin oxide and carbonaceous material, usually ground coal. The temperature is kept between 2200 and 2375F, and from 10 to 12 hr are required to complete the reduction of the tin oxide to metallic tin according to the following equation: $SnO + C \rightarrow Sn + CO$.

The crude tin is further refined (1) by heating in a furnace with a sloping hearth to just above its melting point, where the tin runs into the lower part, leaving most of the unfused metals behind (this process is called *liquation*); (2) by fire-refining, in which the tin is heated to its molten state under oxidizing conditions until the more active impurities become oxidized and are skimmed off; or (3) by electrolytic deposition of pure tin anodes in an acid electrolyte.

Commercial tin has a purity of 99 per cent or better. The impurities include antimony, arsenic, lead, copper, bismuth, iron, silver, and sulphur.

Tin has a brilliant white color with a faint yellowish tint. It is soft and highly ductile; it is malleable at room temperature and cannot be work-hardened at normal temperatures. At very low temperatures, it disintegrates into powder and becomes brittle when heated. It is marketed as ingots weighing from 7 to 100 lb or as "block" tin for tin plate in blocks weighing from 350 to 400 lb.

The atomic weight of tin is 118.70. Its melting point is 449.6F, and its boiling point is 4118F.

Its principal uses are for tin plate, solder, babbitt or bearing metal, collapsible tubes, tin foil, bronze, and chemicals. It is highly resistant to attacks by organic and inorganic substances, and maintains its silver-like luster in atmospheric air.

8–21. Lead. Evidence of the use of lead is found in the earliest recorded history of man. The ease with which its ores could be reduced in the crude furnaces, its softness, and its extreme malleability made it available and adaptable for many uses.

Lead is found in many lands, but the chief producer at the present time is the United States, with Australia, Germany, and Canada following in succeeding order.

Besides a considerable amount reclaimed from scrap, lead is derived from galena, which is a lead sulphate (PbS) and cerussite, a lead carbonate ($PbCO_3$). The most important ore, however, is galena which, when pure, contains 86.6 per cent lead and always contains small amounts of silver, zinc, gold, iron, and sometimes copper. The average lead content of ore deposits is 5 per cent.

The conversion of these ores to metallic lead conforms largely to a pattern followed in the conversion of other metals. First, the ore is concentrated to between 40 and 60 per cent by flotation and is roasted to remove the sulphur and to sinter fine ores. Its reduction to metallic lead is effected by means of carbon and carbon monoxide in a blast furnace similar in principle to the copper blast furnace. Up to 600 tons of lead-base bullion is produced by one of these furnaces every 24 hr.

To refine the lead and recover the gold and silver it may contain, the bullion is melted under oxidizing conditions until most of the impurities (bismuth, arsenic, or antimony) become oxidized and are skimmed off. It is later placed in desilverizing kettles with zinc, in which both gold and silver are soluble. Since lead and zinc are insoluble in both the molten and solid state, they form two distinct layers in the molten bath; and, since the zinc has a lower specific gravity than the lead, it rises to the surface and is skimmed off with the precious metals. The refined lead remains underneath. This is known as the *Parkes process*.

Another method for producing high purity lead for paints and chemicals, known as the *Betts process*, is to suspend the lead bullion as anodes in an electrolyte and deposit the lead on pure lead cathodes while the gold and silver are recovered from the sediment in the bottom of the tank.

Lead is marketed as pigs weighing from 80 to 100 lb and is available in the following several grades: corroding lead, 99.99 per cent pure for making white lead; chemical lead, 99.92 per cent pure for chemical manufacturing industry; and common desilverized lead, which contains up to 0.25 per cent bismuth and is often used for the same purposes as the chemical lead, as well as other uses.

Lead is soft, and is easy to extrude, fabricate, work, forge, and weld by the gas process. Its hardness is increased by additions of tin, cadmium, and antimony. It cannot be work-hardened at ordinary temperatures. Its tensile strength is about 2,000 psi. It has a specific gravity of 11.34 as compared to 8.90 for copper, 7.87 for iron, 7.30 for tin, and 2.70 for aluminum. Its melting point is 621.2F, and it boils at 3171F. When freshly cut, its surface has a bright silver luster which oxidizes to a dull gray. It is unaffected by atmosphere, moisture, and water; and it resists sulphuric acid action. Because of its resistance to the penetration of rays of short wave length, it is commonly used in connection with X-ray and gamma ray work.

Lead is most widely used for solders, babbitt and fusible metals; and it is the best base for type and linotype alloys. In small amounts, it is also added to brasses, bronzes, and aluminum to improve their free-cutting properties. Because of its low melting and high boiling point, it is used as a heating medium in heat-treating steels. It also furnishes sheathing for cables and lining for acid tanks.

QUESTIONS AND PROBLEMS

1. Discuss the relation of ferrous to nonferrous metals in their applications and in their mechanical and physical properties.
2. Compare the smelting of nonferrous and ferrous metals. Discuss the basic principles, cost, and metallurgy.
3. Define "matte," "blister copper," and "tough pitch copper."
4. Discuss the reduction of Cu_2O in copper.
5. What constitutes bronze, and zinc? Give approximate compositions.

6. What is the influence of alloying on the elctrical conductivity, tensile strength, hardness, and melting point of Cu?
7. Why does electrolytic copper not have good weldability?
8. What are the reducing agents for OFHC copper?
9. Name at least six other metals commonly alloyed with Cu.
10. Name two specific applications of each of the alloys of Cu.
11. Define solution heat treatment of Cu-Be Alloys.
12. Compare the role of $CuAl_2$ in Duralumin and Fe_3C in steel.
13. How does the size of the precipitated molecules in Question 12 affect the strength and hardness of the respective metals?
14. What is Alclad, and what is it used for?
15. Discuss the technique of aluminum brazing.
16. Which has the greater load-carrying capacity per unit weight and per unit section; low-alloy steel or Duralumin?
17. Give the compositions of aluminum and zinc sand- and die-castings.
18. What is the significance of the Solvus?
19. What is the principal source of lead?
20. Explain the Parkes and Betts metallurgical processes of lead refining.
21. Give four uses of lead.
22. May lead be hardened by cold-working at normal temperatures? Explain.
23. Give an outline of the smelting of zinc ores.
24. What outstanding property characterizes Cu-Si, Cu-Be, and Cu-Ni alloys?
25. Give the principal uses of tin.
26. List the sources and principal applications of magnesium.

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CHAPTER 9

IRON–IRON CARBIDE DIAGRAM

9–1. Introduction. Inasmuch as the iron–iron carbide diagram indicates the phase changes which occur during the heating and cooling of iron carbon alloys, it is well to interpret the term "phase" as it is applied in metallography. A phase is defined as the physically and chemically homogeneous and distinct part of a system. Pure metal in the molten state is physically and chemically homogeneous with no distinct parts. Water above its freezing point represents one phase. After solidification has begun, another phase (solid) appears, and the system will then have two phases. With the completion of freezing and the disappearance of the melt, there will be but one phase. A phase, however, does not define a physical state, nor is it implied that phases are always determined by the presence of the three states of matter—solid, liquid, or gaseous. A solid state may have more than one phase as may a liquid system. In alloys the important phases are liquid solutions, solid solutions, chemical compounds, and solid metal or metalloids.

Since the diagram indicates the temperature-composition relation, or phase changes, and the various lines define the area within which certain phases are stable, we may now consider the characteristic properties of solid phases which we find during temperature variations in iron carbon alloys. These consist of (1) ferrite, metallic iron, (2) cementite, a chemical compound, and (3) austenite, a solid solution.

9–2. Ferrite. Ferrite is soft, ductile, and practically carbon free. Its solubility for carbon decreases from a maximum of 0.04 per cent at 1333F to 0.008 per cent at room temperature (as shown by *PQ* on the diagram, Fig. 9–6). It has a tensile strength of about 40,000 psi. Its allotropic form is known as alpha, and it crystallizes in the body-centered cubic system. It is also magnetic at normal temperatures (below A_2). Its hardness remains unaltered by heat treatment and, after etching with dilute picric or nitric acid and alcohol, it appears under the microscope as the white constituent in steels of less than 0.83 per cent carbon after a slow cool from the curve *GS* or the ferrite solubility limit. Primary ferrite is precipitated from the gamma solid solution as excess or *free* ferrite in all steels of less than 0.83 per cent carbon. The structure of practically pure iron is shown in the photomicrograph, Fig. 9–1.

9–3. Cementite. Cementite is a chemical compound composed of iron and 6.67 per cent carbon. In common with other intermetallic compounds, cementite is characterized by a high hardness and extreme brittleness. In contrast to ferrite, whose hardness is about 80 Brinell,* the hardness of cementite is approximately 1000. Evidence of its extreme hardness is the difficulty of machining white-iron castings, in which it is a major constituent. Because of its brittleness, little is known of the tensile strength of pure cementite, since practical difficulties would be encountered in applying tension loads uniformly.

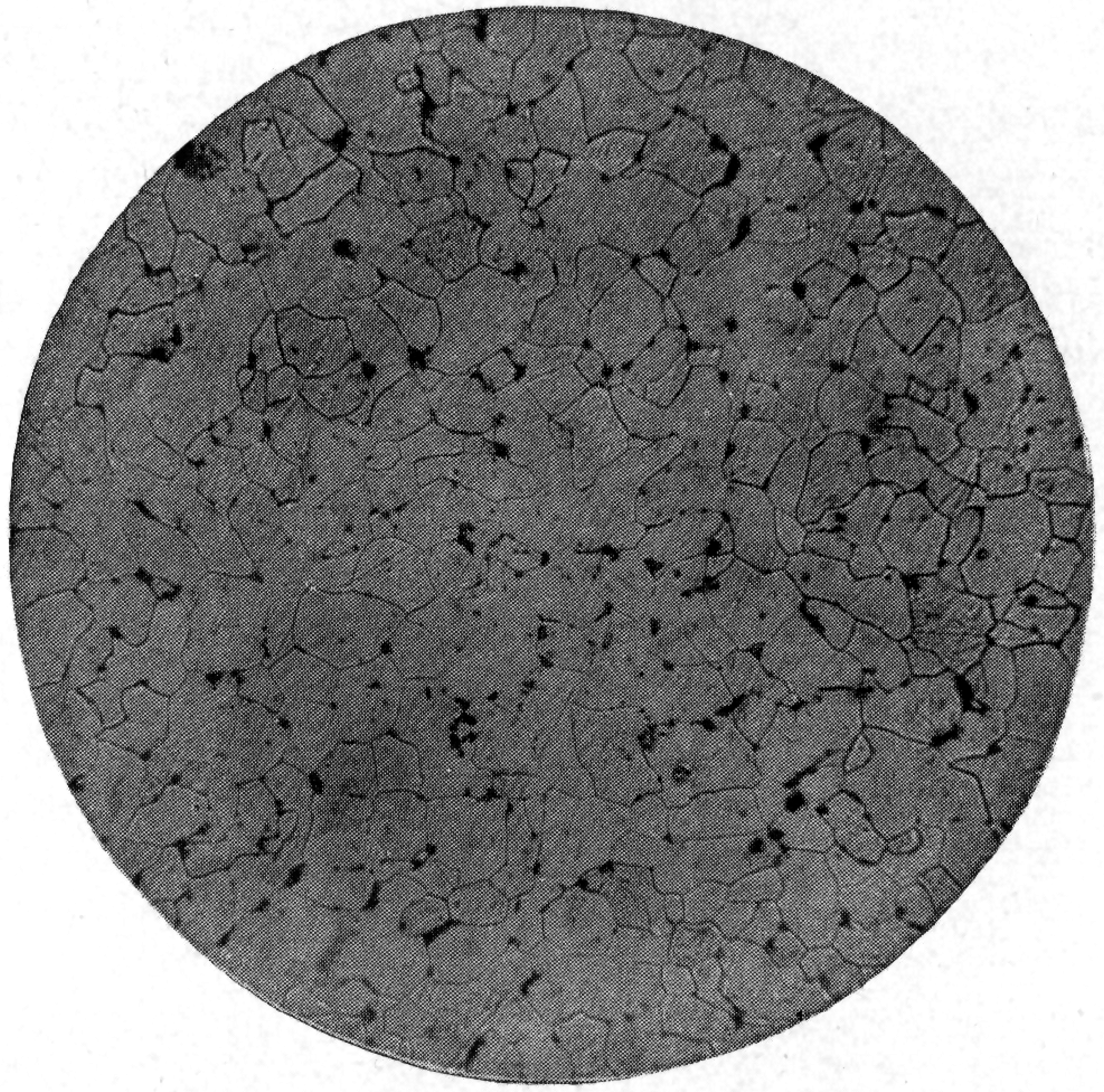

FIG. 9–1: Photomicrograph of dead-soft steel, showing crystalline grain structure. Dark areas are impurities. ×100. (Courtesy of Dr. R. L. Dowdell, School of Mines, University of Minnesota.)

In all slowly cooled steels containing over 0.83 per cent carbon, cementite is found as a grain boundary network (Fig. 9–2) or as needles. In pearlite it is found as parallel plates (lamellar) or as rounded particles or spheroids, as shown in Figs. 10–5 and 10–6. Cementite is soluble in gamma iron but is practically insoluble in alpha ferrite. When well distributed, cementite is a source of increased strength in steels. It also determines the degree to which steels respond to heat treatment.

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*On the basis of the commonly accepted formula of $TS = BHN \times 500$, the strength of cementite is approximately 500,000 psi.

9–4. Austenite. A solid solution in which carbon (or carbide) and other elements are soluble in gamma iron is known as austenite. Its carbon (or carbide) solubility varies from a maximum of 1.70 per cent at 2066F to 0.83 per cent at about 1333F, as discussed later. Austenite is a solid phase of all steels and, unless arrested by alloying elements, its stability is confined to the region above *GSE* on the diagram in Fig. 9–6. Even when very drastic cooling rates are used, as in the quenching of high-carbon and low-alloy steels, only a small percentage of austenite is retained at normal temperatures. Alloyed steels* which remain austenitic are relatively soft when subjected to the usual hardness tests but, because of their great work-hardening properties, become difficult to machine. They are very resistant to most abrasive wear, especially when subjected to peening action. Austenite is also nonmagnetic.

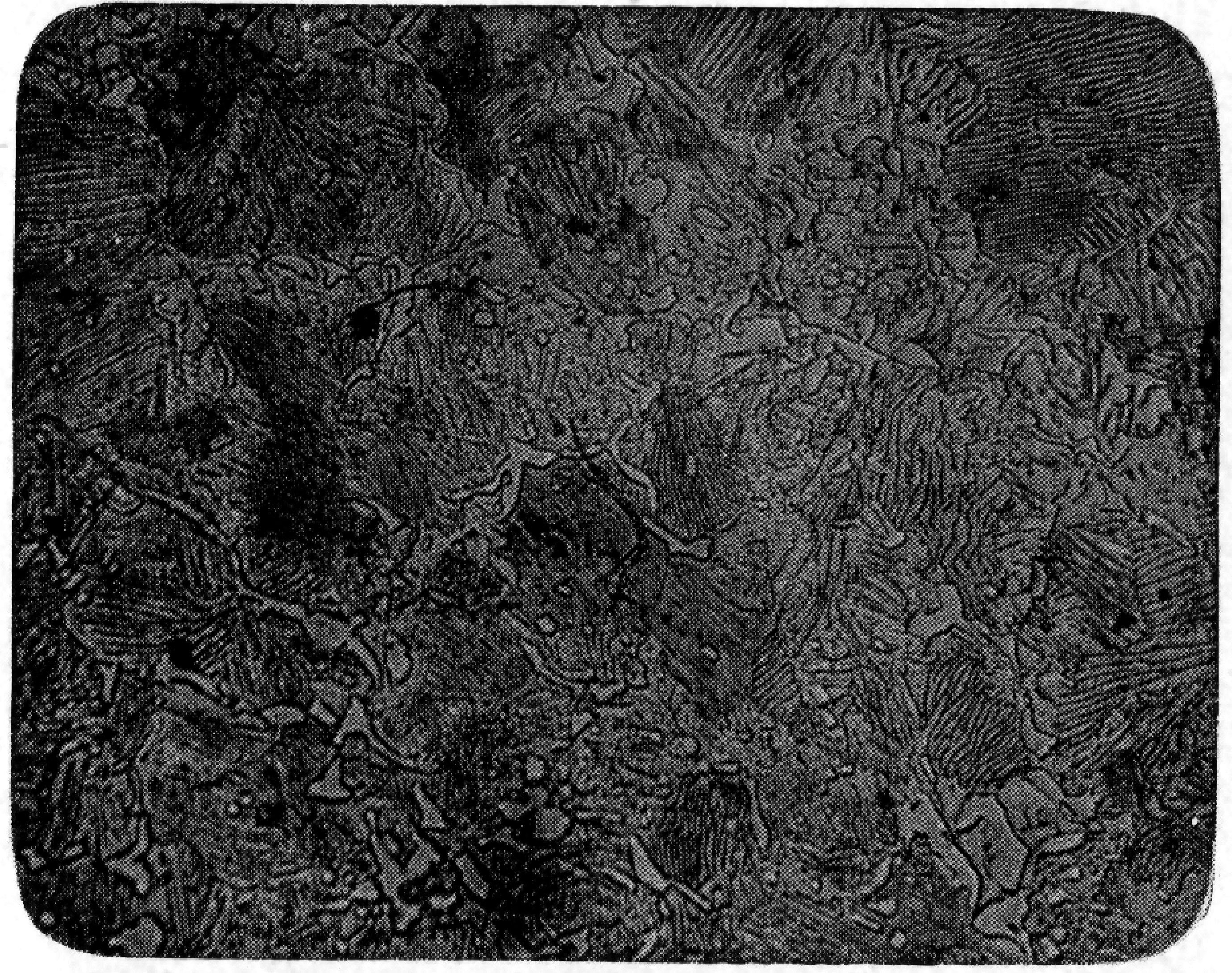

FIG. 9–2. Photomicrograph of annealed hypereutectoid steel, showing excess or free cementite (white areas) and pearlite. ×500. (Courtesy of Dr. R. L. Dowdell, School of Mines, University of Minnesota.)

9–5. Pearlite. Although not a phase, pearlite is composed of two phases—ferrite and carbide, which form at a constant temperature when simultaneously precipitated from the gamma solid solution at the *PSK* or eutectoid temperature. Pearlite is present as a microconstituent of all slowly cooled steels. Its normal structural pattern is formed by alternate thin plates of Fe and Fe_3C and is called lamellar pearlite. When microscopically resolved at a high magnification, its structure resembles a fingerprint. As pointed out later, pearlite is formed as a final stage in the decomposition of austenite or gamma → alpha transformation at the eutectoid temperature on slow cooling. With faster cooling rates, such as those obtained by an air cooling, the gamma-alpha transformation temperature is lowered with resultant finer and stronger pearlite. The tensile strength of steels of 100 per cent pearlite ranges from 100,000 to 150,000 psi depending on the fineness of the structure, with elongation of 20 to 10 per cent respectively. It derives its name from the similarity of its appearance to mother-of-pearl after etching. It is composed of 88 parts Fe and 12 parts Fe_3C by weight. The relative proportion of pearlite to the ferrite with higher percentages of C is shown in Figs. 9–3, 9–4, and 9–5.

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*Hadfield's 14 per cent manganese steel.

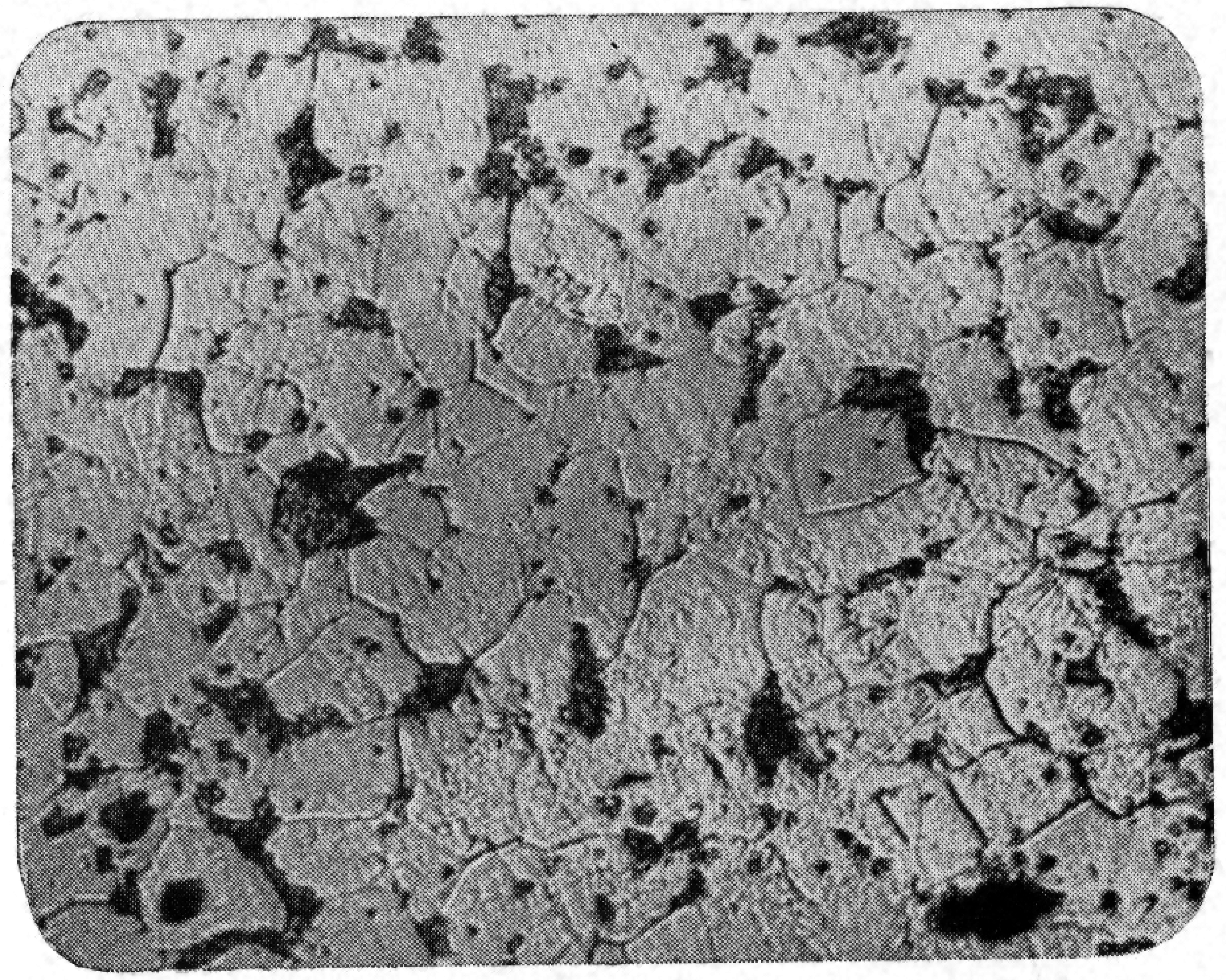


FIG. 9–3. Photomicrograph of 0.15 per cent carbon steel. Dark areas pearlite; white areas ferrite. ×100. (Courtesy of Dr. R. L. Dowdell, School of Mines, University of Minnesota.)

The discussion of equilibrium or constitution diagrams heretofore has centered principally on transformations associated with changes in physical state liquid ⇄ solid. The alloys exhibit no thermal reactions other than those related to the effects of latent heat of fusion. The iron–iron carbide diagram represents not only changes affecting physical states but also significant changes involving solid constituents. Since such transformations are accompanied by either endothermic or exothermic reactions, temperatures at which these phenomena occur are designated *critical* temperatures. Furthermore, some of the transformations which occur at these temperatures are factors which determine the response of steels to heat treatment, since solubility, diffusion, precipitation, and recrystallization are involved.

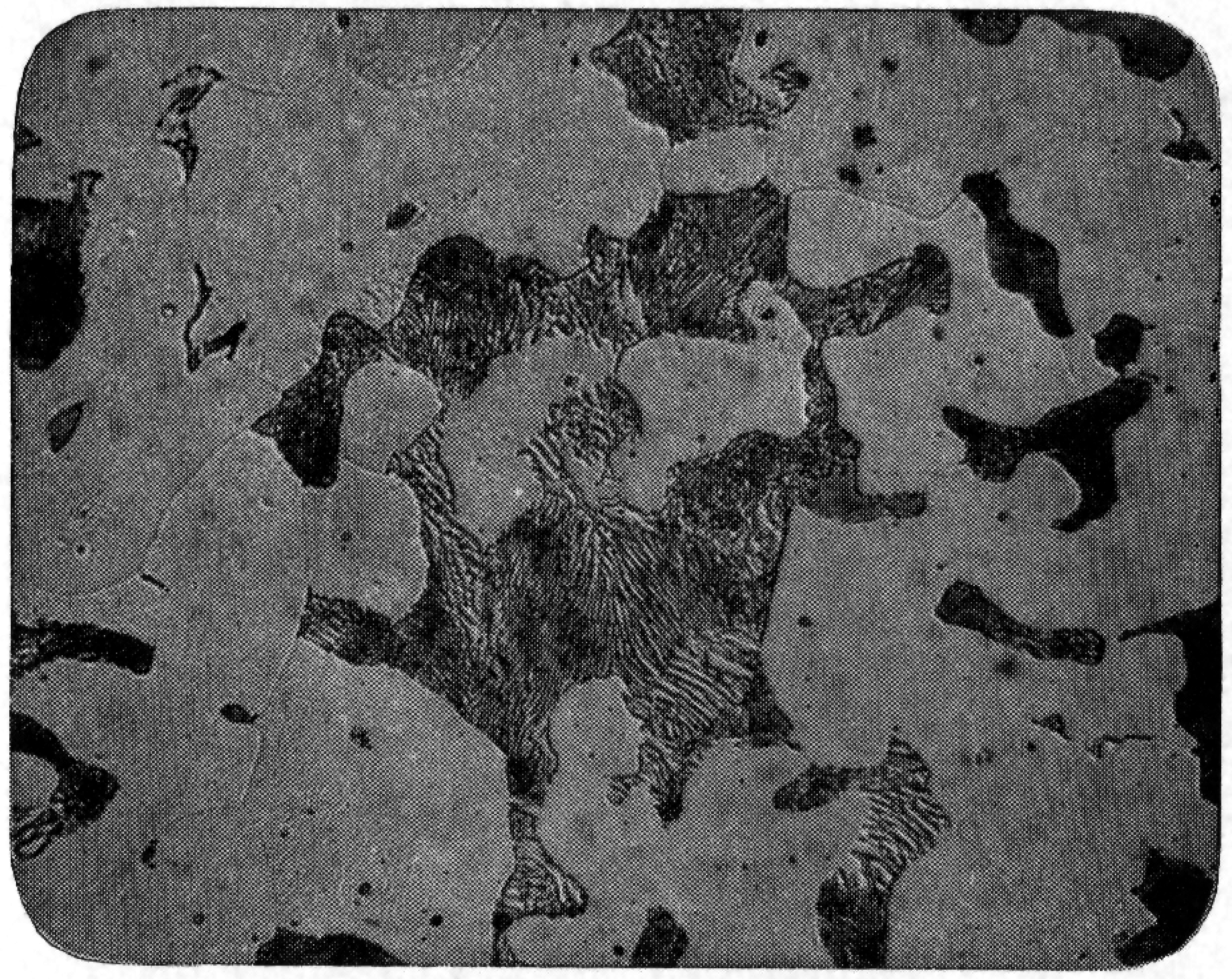


FIG. 9–4. Photomicrograph of 0.25 per cent carbon steel. Pearlite and ferrite. ×500. (Courtesy of Dr. R. L. Dowdell, School of Mines, University of Minnesota.)

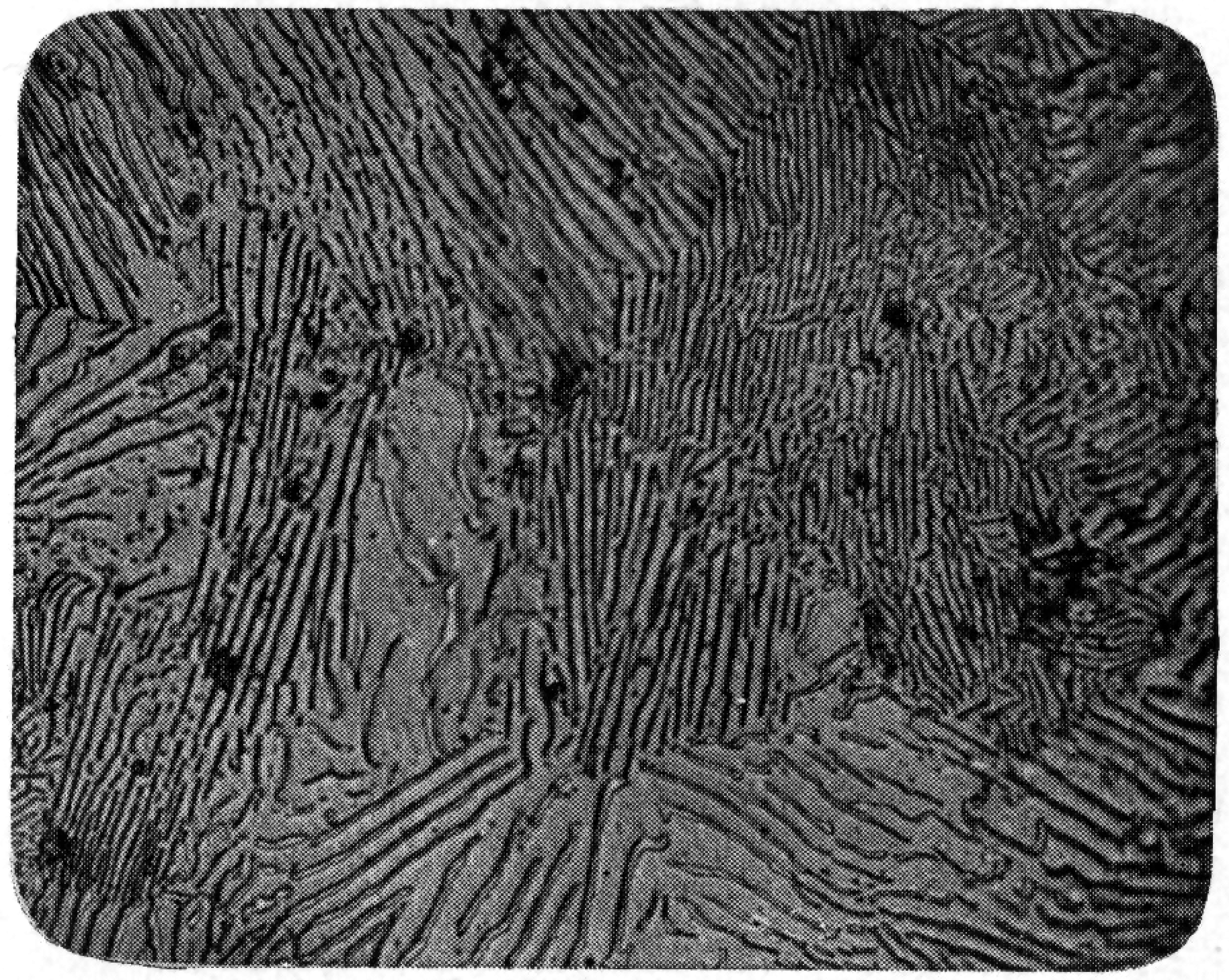


FIG. 9–5. Photomicrograph of eutectoid steel (annealed), showing the structural formation of pearlite. ×1000. (Courtesy of Dr. R. L. Dowdell, School of Mines, University of Minnesota.)

9–6. Designations of Critical Temperatures. The alpha → gamma transformation in steels is accompanied by an endothermic reaction while the gamma → alpha transformation is characterized by an exothermic effect. Since both thermal reactions interrupt normal heating and cooling rates, the temperatures at which these transformations take place are identified by the letter *A* as an abbreviation of arrest. Those transformations which occur during heating are further identified by *c*, while, to those which occur during cooling, the letter *r* is added. Thus the critical temperatures on heating are designated *Ac* and those on cooling *Ar*.

As shown by the diagram in Fig. 9–6, curve *GS*, which indicates the beginning of the gamma → alpha transformation on cooling for those alloys containing less than 0.83 per cent carbon, varies inversely as the percentage of carbon, while the temperature denoting the completion of the transformation remains nearly constant. Since these alloys, therefore, have two critical temperatures, they are designated A_3 and A_1, respectively, for the beginning and the ending of the gamma → alpha transformation. The subscript *3*, rather than *2*, is applied to the upper critical *GS*, because alpha ferrite, without undergoing an allotropic change, loses its magnetism at about 1420F which has been designated A_2 or beta transformation. This temperature, however, has no significance in heat treatment and is, therefore, frequently not shown on the diagram.

Because the A_3, A_2, and A_1 points merge when the composition reaches 0.83 per cent carbon, the unified critical temperature is designated $A_{3\text{-}2\text{-}1}$, or more commonly A_1. The *Ar* criticals occur at lower temperatures than the corresponding ones on heating because of a hysteresis or atomic inertia as the solid solution austenite decomposes into its constituents—ferrite and carbide (or carbon).

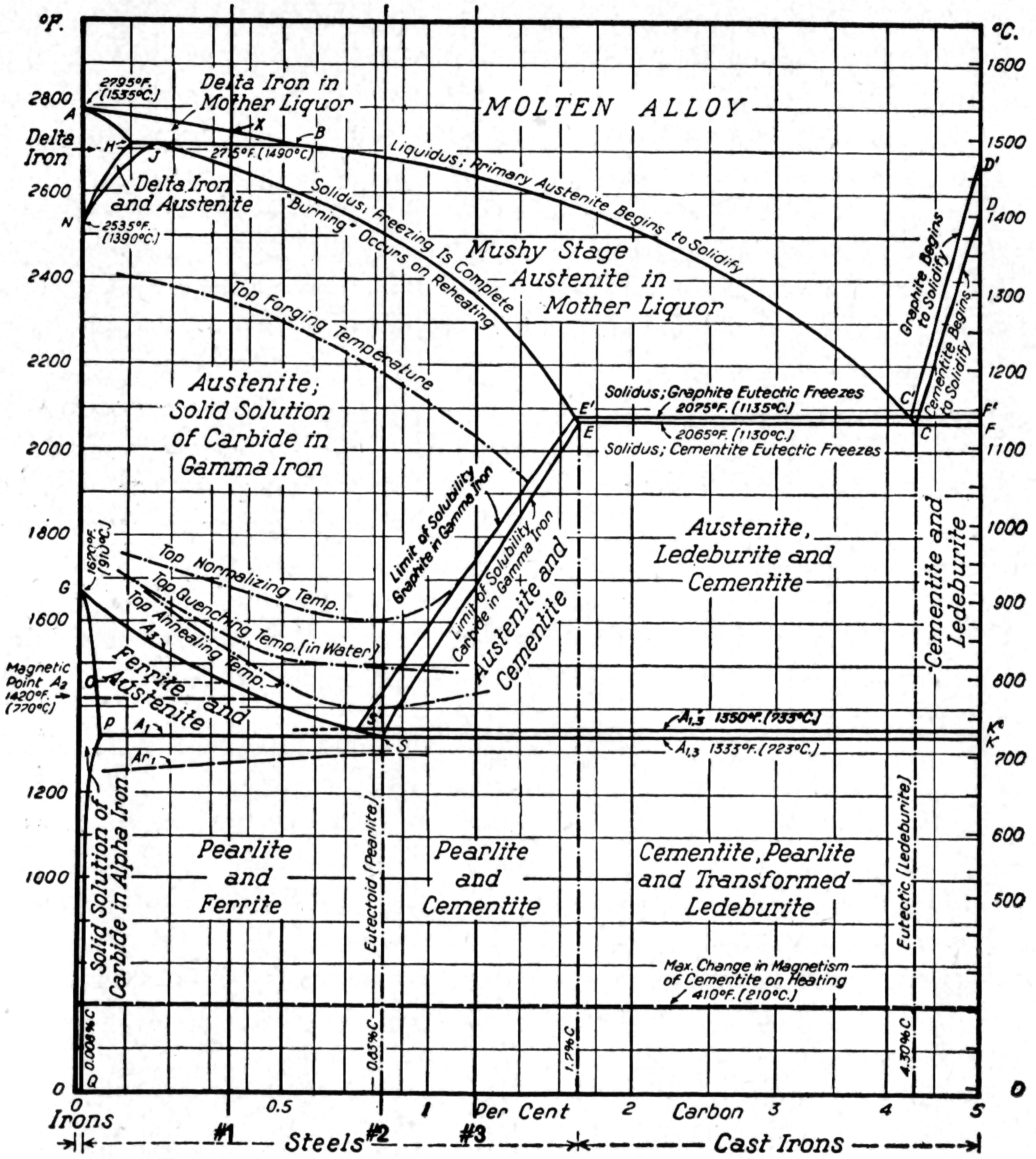
The *Acm* designates the temperature at which cementite precipitates from austenite on slow cooling and goes into solution on heating.

9–7. Classification of Iron Carbon Alloys.

Plain carbon steels containing less than 0.83 per cent carbon are known as hypoeutectoid; with a composition of 0.83 per cent carbon, they are called eutectoid; and from 0.83 to 1.7 per cent carbon, they are called hypereutectoid. Likewise, cast-iron alloys containing from 1.7 to 4.3 per cent carbon are called hypoeutectic, alloys of 4.3 per cent carbon are called eutectic; and alloys with over 4.3 per cent are called hypereutectic.

The iron–iron carbide diagram has features comparable to the types shown in Figs. 2–6 and 2–8. It differs from these, however, in that one of the constituent elements exists in two forms—graphite and the chemical compound, iron carbide.

As shown by the diagram, alloys containing less than 1.7 per cent carbon are referred to as steels, while those represented by values in excess of this are referred to as cast-irons. This division is based on the solubility


°F.
°C.
2800
2600
2400
2200
2000
1800
1600
1200
1000
0
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
0
Delta Iron
A
H
J
N
B
X
G
P
Q
S
S'
E
E'
C
C'
D
D'
F
F'
K
K'
2795°F. (1535°C.)
2715°F. (1490°C.)
2535°F. (1390°C.)
1670°F. (910°C.)
Magnetic Point A_2 1420°F. (770°C)
Delta Iron in Mother Liquor
MOLTEN ALLOY
Delta Iron and Austenite
Liquidus; Primary Austenite Begins to Solidify
Solidus; Freezing Is Complete
"Burning" Occurs on Reheating
Mushy Stage Austenite in Mother Liquor
Top Forging Temperature
Graphite Begins to Solidify
Cementite Begins to Solidify
Austenite; Solid Solution of Carbide in Gamma Iron
Solidus; Graphite Eutectic Freezes 2075°F. (1135°C.)
2065°F. (1130°C.) Solidus; Cementite Eutectic Freezes
Limit of Solubility Graphite in Gamma Iron
Limit of Solubility Carbide in Gamma Iron
Austenite and Cementite
Austenite, Ledeburite and Cementite
Cementite and Ledeburite
Top Normalizing Temp.
Top Quenching Temp. (in Water)
Top Annealing Temp.
A_3
A_1
Ar_1
Ferrite and Austenite
$A_{1,3}$ 1350°F. (733°C.)
$A_{1,3}$ 1333°F. (723°C.)
Solid Solution of Carbide in Alpha Iron
Pearlite and Ferrite
Eutectoid (Pearlite)
Pearlite and Cementite
Cementite, Pearlite and Transformed Ledeburite
Eutectic (Ledeburite)
Max. Change in Magnetism of Cementite on Heating 410°F. (210°C.)
0.008% C
0.83% C
1.7% C
4.30% C
0
0.5
1
2
3
4
5
Per Cent Carbon
Irons
#1
#2
#3
Steels
Cast Irons

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Delta iron region and solidus by Frank Adcock, *Journal*, Iron and Steel Institute, 1937-I.

Forging and heat-treating temperatures from Recommended Practices, 1939 ASM Metals Handbook.

Solidus in Iron-Graphic System according to Kaya, Honda and Endo, *Science Reports*, Tohoku Imperial University, 1925 and 1927.

Ar_1 according to Hoyt and Dowdell, *Metals and Common Alloys*, for cooling rates of 1C in 3 sec.

Line *GPQ* according to J. H. Whiteley, *Journal*, Iron and Steel Institute, 1936.

FIG. 9–6. Iron–iron carbide equilibrium diagram.

of carbide in gamma iron which reaches a maximum of 1.7 per cent at 2066F and decreases as shown by *ES* or the *Acm* to 0.83 per cent at 1333F.

Studying these separate divisions of the diagram and relating them to preceding discussion of equilibrium diagrams makes the interpretation of Fig. 9–6 relatively simple.

If we assume an alloy of 4.3 per cent carbon, it is seen that above the liquidus *ABCD* it consists of one phase—the melt. Freezing or solidification takes place at point *C* when the simultaneous precipitation of gamma iron and cementite takes place, forming a eutectic mixture called ledeburite.

Alloys containing less than 4.3 per cent carbon start to solidify at the liquidus curve *ABC* with the separation of primary crystals of gamma iron or austenite solid solution. Solidification is completed at the eutectic temperature when the gamma iron becomes surrounded by the eutectic which contains 4.3 per cent carbon.

The cooling of alloys containing more than 4.3 per cent carbon proceeds in a similar manner with the precipitation of cementite from the melt beginning at *CD* and ending at the eutectic temperature, with the last melt to freeze having a composition of 4.3 per cent carbon. Below the eutectic, excess cementite continues to separate out in any alloy until the temperature drops to 1333F (A_1), when the remaining austenite transforms into pearlite. The microstructure will, therefore, consist of pearlite and cementite.

The portion of the diagram indicating phase changes in carbon steel is shown in simplified form in Fig. 9–7. By comparing the two divisions of the diagram in Fig. 9–6 as outlined by *GSE* and *ABCD*, it is seen that a minimum temperature is indicated at which a melt of composition *C* and a solid solution of composition *S* can remain stable.

For further interpretation, let us study the cooling of three alloys as represented by concentration verticals #1, #2, and #3 on the diagram, Fig. 9–6. Alloy #1 containing 0.35 per cent carbon begins to solidify at point *X* on the liquidus *ABC* with the formation of delta iron* (body-centered cubic) crystals which, at a temperature of 2715F, undergo an allotropic change, becoming nonmagnetic gamma iron. Solidification of gamma solid solution is complete at the solidus *AHJEF*. Except for a slight growth of the austenite grains, no further change takes place until the temperature reaches curve *GS* when nonmagnetic or paramagnetic alpha iron of composition *O* begins to separate out from the austenite. At the A_2, or "magnetic" critical, the alpha iron crystals become ferromagnetic without undergoing an allotropic change affecting lattice structure. The separation of alpha ferrite continues until *PS* is reached. While the composition of the ferrite (solid solution) varies along *GP*, the composition of the austenite also changes along *GS* until the residual austenite, stable just above *PS*, contains 0.83 per cent carbon or the eutectoid composition which transforms at constant temperature into two phases—alpha ferrite and cementite. At the eutectoid temperature and under conditions of slow cooling, these two phases form the mechanical mixture called pearlite. Below *PS* no further change takes place except that the solubility of carbon in alpha iron decreases as shown by *PQ*. The structural constituents will consist of ferrite and pearlite in the proportions of 57.8 per cent ferrite and 42.2 per cent pearlite.

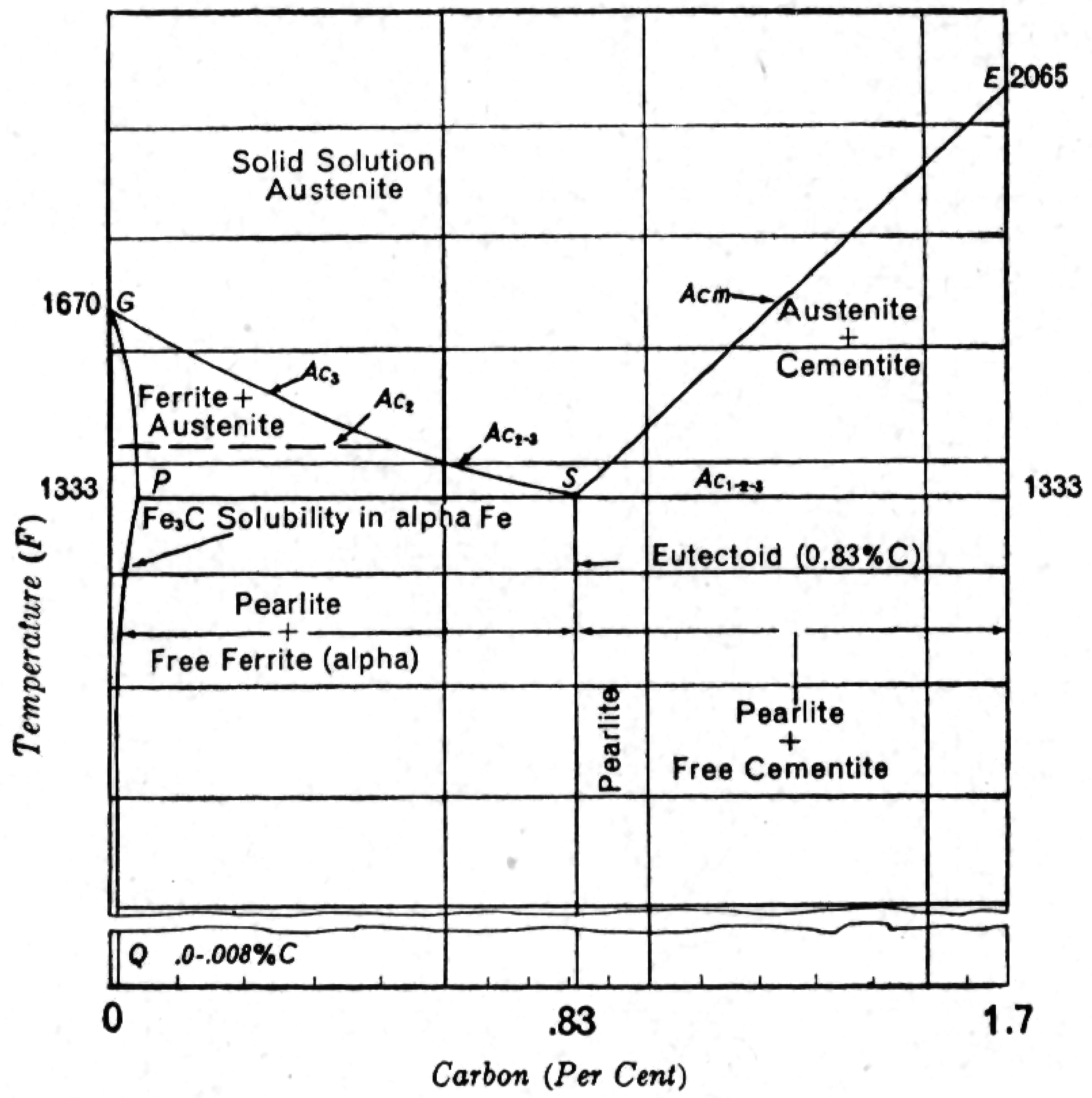

Fig. 9–7. Simplified form of iron–iron carbide diagram, showing temperature ranges which specifically apply in heat treatment of steels.

$$\frac{0.83-0.35}{0.83} \times 100 = 57.8 \text{ Fe} \qquad \frac{0.35}{0.83} \times 100 = 42.2 \text{ P}$$

The cooling characteristics of alloy #2, which is composed of 0.83 per cent carbon, are similar to those of alloy #1 until the eutectoid temperature or *PS* is reached; then the austenite transforms at a constant temperature into ferrite and cementite. Below *PS* the alloy cools exactly like alloy #1. Since all the alpha ferrite and carbide precipitated simultaneously, the structure will consist of 100 per cent lamellar pearlite or the eutectoid.

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*The delta phase is stable only in the range 2535F to 2795F and is, therefore, never present in carbon and low-alloy steels in the heat-treating temperature range. Further discussion seems unwarranted.

TABLE 9–1

SUMMARY OF STRUCTURAL TRANSFORMATIONS DURING HEATING AND SLOW COOLING OF HYPOEUTECTOID, EUTECTOID, AND HYPEREUTECTOID STEELS

Critical Designations	Hypoeutectoid A	Eutectoid B	Hypereutectoid C
Ac_1	Beginning of transformation of pearlite to austenite.	Transformation of *all* pearlite to austenite.	Same as B.
Ac_2	End of magnetism of ferrite.	. . .	. . .
Ac_3	alpha–gamma transformation complete.	. . .	. . .
Acm	. . .	. . .	Completion of solution of cementite in austenite.
Acm	. . .	. . .	Precipitation of cementite from austenite begins.
Ar_3	Precipitation of ferrite from austenite begins.	Transformation of all austenite to pearlite.	End of precipitation of Fe_3C from austenite and formation of pearlite.
Ar_2	Transformation of nonmagnetic iron to magnetic ferrite.	. . .	. . .
Ar_1	Precipitation of ferrite ends and residual austenite changes to pearlite.	. . .	. . .

The cooling of alloy #3, containing 1.2 per cent carbon, is similar to that of alloys #1 and #2 until the *Acm* or *SE* temperature is reached. Here, in contrast to the precipitation of ferrite which takes place at the A_3 in hypoeutectoid steels, in hypereutectoid steels, the cementite is progressively precipitated, beginning at the *Acm* and continuing until the eutectoid temperature or *PSK* is reached. The composition of the austenite changes along *SE* until, at the Ar_1 temperature, it contains 0.83 per cent carbon in solution. At *PSK* an arrest in the cooling is noted, caused by a reaction similar to that described for alloys #1 and #2, i.e., the austenite transforms into ferrite and cementite which form pearlite. The microstructure at room temperature will, therefore, consist of cementite, precipitated between the *Acm* and *PSK*, and pearlite. Their respective proportions will be:

$$\text{Cementite} = 100 \times \frac{1.20 - 0.83}{6.67 - 0.83} = 6.3 \text{ per cent;}$$

$$\text{Pearlite} = 100 \text{ per cent} - 6.3 \text{ per cent} = 93.7 \text{ per cent.}$$

The structure of dead-soft steel (C 0.08 per cent) is shown in Fig. 9–6. The dark areas are impurities. The relative proportions of ferrite and pearlite with increasing carbon is shown by photomicrographs in Figs. 9–3, 4, and 5.

QUESTIONS AND PROBLEMS

1. Define "phase."
2. Compare the NaCl + H_2O diagram and the iron–iron carbide diagram.
3. In what respects is austenite similar to the steel in a molten state?
4. What is the principal significance, from a heat-treating standpoint, of the alpha ⇆ gamma transformation?
5. What is the influence of increased amount of carbide on the tensile and impact strength of steel?
6. Normally, what is the form of the carbide in slowly cooled steels of 0.60 and 1.50 per cent C?
7. Compare changes in physical state liquid ⇆ solid and alpha ⇆ gamma transformations.
8. Define "steel" and "cast-iron."
9. Discuss phenomena occurring at the eutectic and eutectoid temperatures.
10. Describe in detail the slow cooling of steel containing 0.50 and 1.3 per cent C from the molten state to normal temperature.
11. Compute the amount of the structural constituents in a 0.70 per cent C steel, cooled from above the Ar_3 temperature.
12. Compute the amount of the phases present in the steel of Question 11.

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CHAPTER 10

THE HEAT TREATMENT OF STEELS

10–1. Introduction. Within wide limits of compositions, steels are classified as plain carbon steels and alloy steels. Since small amounts of alloy elements, derived from raw materials, are often present in the basic iron carbon alloys, the division between carbon and alloy steels is not sharply drawn and they are not satisfactorily defined. However, alloy steels may be said to contain elements which have been added purposely, and in sufficient amounts, to impart properties not obtainable with plain carbon steels.

Carbon steels are usually classified as shown in Table 10–1, while the alloy group is subdivided on the basis of the predominating element.

TABLE 10–1

Classification and Typical Analyses of Plain Carbon Steels (Per Cent)

	Dead-Soft	Mild Steel	Medium-Carbon	Low-Carbon Tool Steel	High-Carbon Tool Steel
C.	0.08–0.15	0.15–0.30	0.30–0.60	0.60–0.80	0.80–1.50
Mn.	0.30–0.60	0.30–0.60	0.60–0.90	0.60–0.90	0.60–0.50
P.	0.040 max.	0.040 max.	0.040 max.	0.040 max.	0.040 max.
S.	0.050 max.	0.050 max.	0.050 max.	0.050 max.	0.050 max.

Nickel-chromium and chromium-nickel contain similar elements but are considered different steels because of the amount of the respective elements and, consequently, their influence on the properties.

Heat-treating processes applied to plain carbon steels are applicable also to the alloy steels, although temperatures and techniques by which the latent properties of carbon steels are developed are slightly modified by the presence of alloys. For example, in order to harden fully, plain carbon steels must be cooled rapidly in water from their respective critical temperatures, or in some other aqueous solution. The hardness of alloy steels may, generally, be developed fully by cooling at a slower rate, such as that obtained by quenching in oil, since the elements present increase the sluggishness of the austenite and the transformation takes place at progressively lower temperatures with increasing amounts of the alloys. That they may thus be hardened by a slow cool greatly simplifies the problems of the heat-treater. Other alloys may harden sufficiently when cooled in a blast of cold air. Solution temperature also is usually influenced—carbide-forming elements tend to raise it while those alloys soluble in the solvent (ferrite) have an opposite influence.* The carbides of some of the elements are more stable than those of iron and, therefore, require a higher temperature for their complete diffusion in the austenite.† Certain elements such as Mn, Cr, and Ni also reduce the normal carbon content of the eutectoid so that pearlite in annealed and normalized steels contains considerably less than 0.83 per cent carbon.

Carbon or carbide, Fe_3C, is the predominating element in unalloyed steel. The hardness, tensile strength, and ductility of steel in the annealed condition, as well as its response and adaptability to all forms of heat treatment, are largely determined by the amount of carbon. Carbon also fixes the hardness limitations of low-alloy steels, as shown in Fig. 10–1. With increasing amounts of carbon, the tensile strength of hypoeutectoid steels increases sharply up to 0.83 per cent, while above this value the strength increases more gradually. Weldability, as described in later chapters, is adversely affected by carbon.

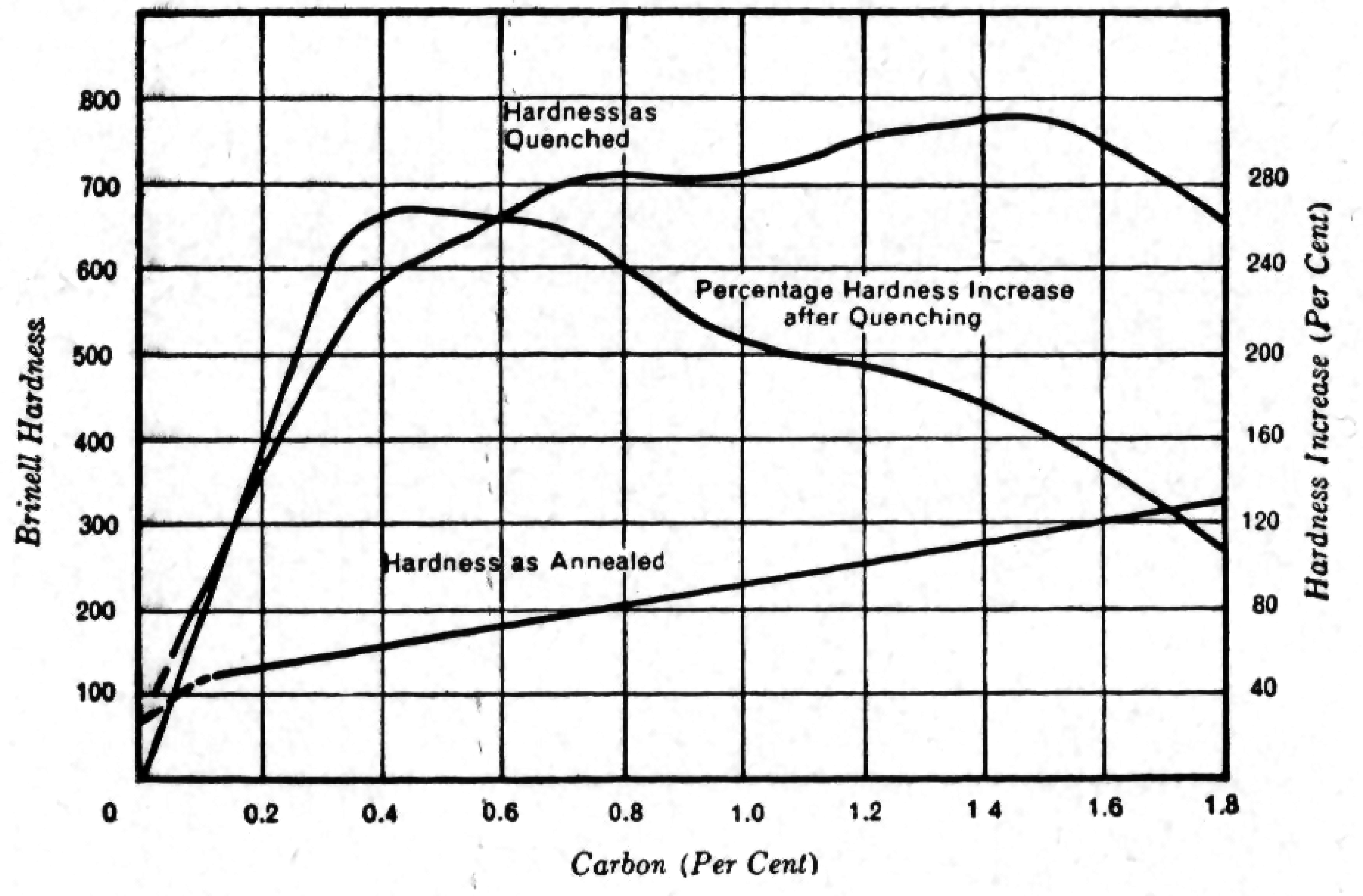

FIG. 10–1. Relation between Brinell hardness and carbon content of annealed and water-quenched steels. (Adapted from *The Alloys of Iron and Carbon*, Vol. I, by Epstein.)

Manganese and silicon, added as deoxidizers, are present in solid solution in small amounts in all commercial steels, but their influence upon the response of steels to heat treatments and upon their mechanical properties is insignificant. Phosphorus and sulphur, as residual impurities, are kept to the allowable maximum, especially in high-grade steels, because they tend to reduce malleability and impact resistance. These values are given in Table 10–1.

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*Each 0.01 per cent of manganese and nickel lowers the Ac_3 0.5 and 0.4F, respectively, so that high Mn and high Ni steels are wholly austenitic at normal temperatures.

†High-speed steels containing 18 per cent W, 4 per cent Cr, 1 per cent V, with from 0.70 to 0.80 per cent C, are quenched for hardening from a temperature close to the solidus or 2200 to 2350F.

The adaptability of steels for industrial applications is governed not alone by the *amounts* of the various chemical constituents listed, but also by their physical *distribution* and *form* as these have been influenced by previous heat treatments or mechanical working. Therefore, in order to make the most effective use of metals, it is important to understand the conditions which may influence their behavior in service.

In a preceding chapter a study was made of the influence of a slow cooling rate (under equilibrium conditions) on the phases present at normal temperatures. If similar steels were cooled rapidly from the austenitic temperature, both the form and distribution of the phases, ferrite and cementite, would be altered; and tests would indicate that the mechanical and physical properties of the steels were greatly different from those produced under equilibrium conditions. This difference in properties would vary in direct proportion to the difference in cooling velocities. In steels cooled quickly, the tensile strength, yield strength, and hardness would be found to have increased considerably while the ductility and machinability would be correspondingly reduced. Heat treatment is largely a matter of exercising control over the two factors of temperature and cooling time or rate.

It is now obvious that the latent potentialities of steels for a wide range of engineering applications may be developed most fully through several forms of heat treatment, principally involving cooling rates selected to bring into being certain desirable and suitable structures. Involved in these structural changes are formation of solid solutions, recrystallization, precipitation, grain size, and release or setting up of internal stresses.

Therefore, heat treatment is defined as an operation or combination of operations involving the heating and cooling of a metal or alloy in the solid state for the purpose of obtaining certain desirable conditions or properties.

The principal processes are (1) annealing, (2) normalizing, (3) hardening and tempering or drawing, and (4) casehardening or surface-hardening. Several heat-treating processes are shown diagrammatically in Fig. 10–2.

10–2. Annealing. Heating of steel above the Ac_3 and holding for a sufficient length of time to obtain complete homogenization of the constituents followed by a restricted cooling is called annealing. Usually the cooling takes place in the furnace after the heating is completed. Where it is inconvenient or impractical to use the furnace for this purpose, a sufficiently slow cooling rate may be obtained by covering in a suitable box with dry sand, lime, ashes, asbestos packing, or other insulating material.

The objectives of annealing may include some or all of the following: (1) to soften hardened steel for the purpose of machining, etc.; (2) to increase ductility of cold-worked metals; (3) to refine the grain structure; (4) to relieve internal stresses; (5) to produce a structure desirable for hardening or cold-working.

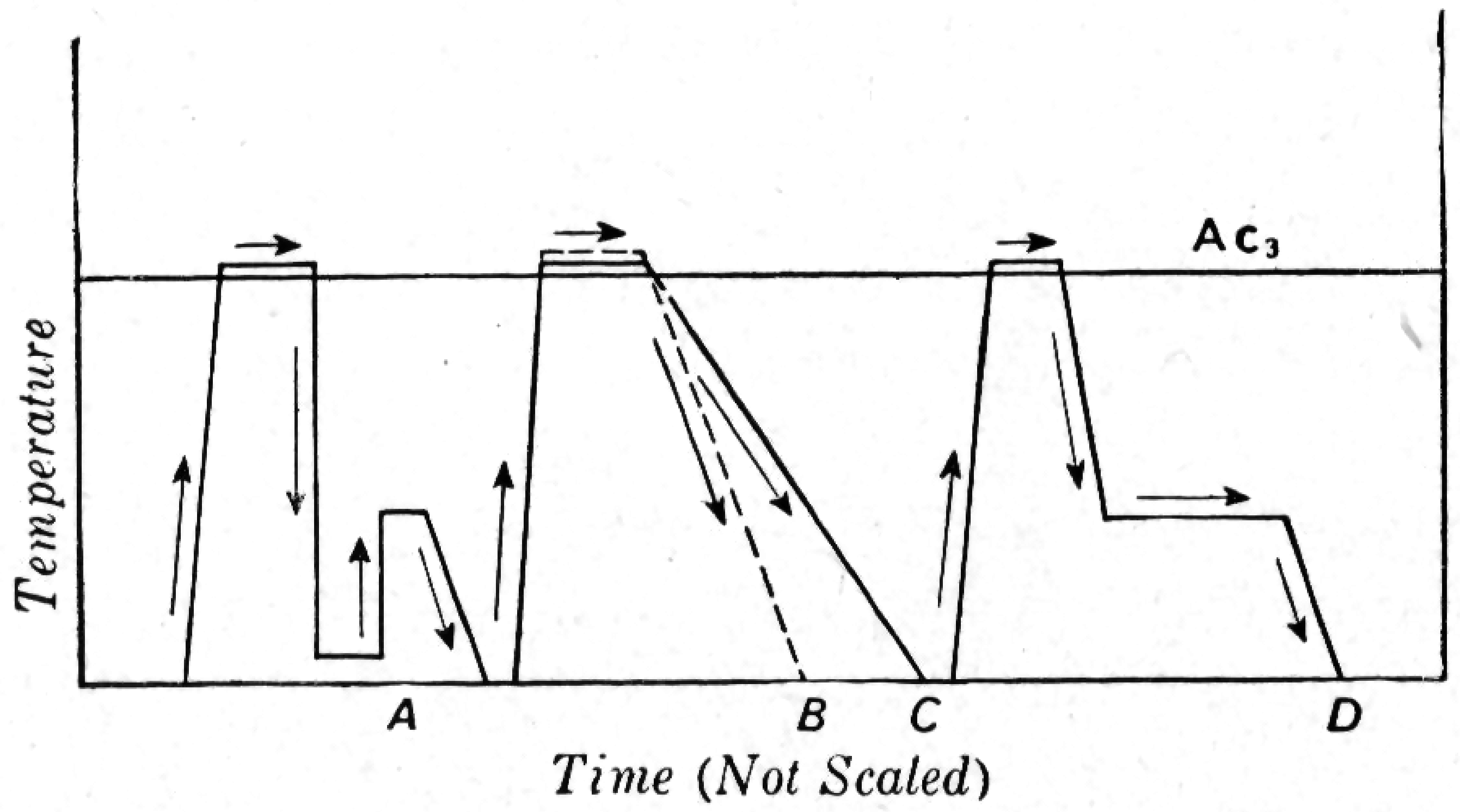


FIG. 10–2. Temperature-cooling time relation for various heat-treating processes: *A*, hardening and tempering; *B*, normalizing; *C*, annealing; *D*, austempering

Similar to other heat-treating processes, the factors of temperature and cooling time must be correlated closely with the volume and surface area of the parts if the conditions relative to structure and mechanical properties are to be realized.

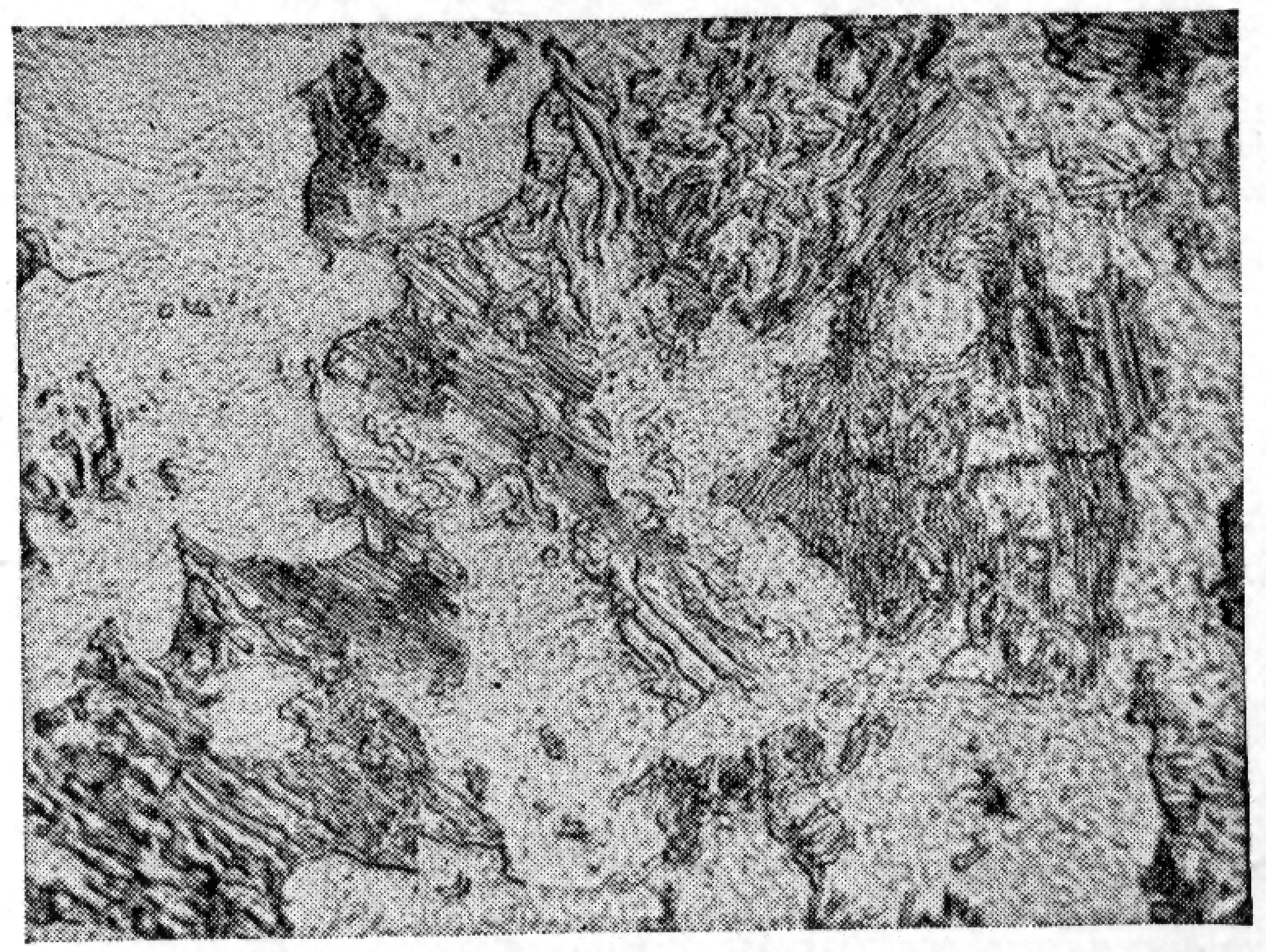


FIG. 10–3. Annealed carbon steel, showing pearlite and ferrite. Cooled in furnace from above Ac_3. Carbon = 0.54 per cent. ×500.

The slow cooling of hypoeutectoid steels from above the Ac_3 temperature produces the microconstituents ferrite and coarse lamellar pearlite, shown in Fig. 10–3. Long-time holding at temperatures just below the Ar_1 should result in spheroidizing the carbide. After cooling slowly from above the Acm, the structure of hypereutectoid steels will consist of pearlite grains surrounded by a continuous network of carbide. This condition induces brittleness, increases machining difficulties, and renders the steel much less responsive to a full hardening. Toughness is, therefore, not always a corollary of a slow cooling rate. Similar steels cooled in still air (normalizing) exhibit greater toughness than when annealed, because the faster cooling between the Acm and Ar_1 results in the carbide being distributed as needles or spines and with less separation of a carbide network.

Sheets and wire that have been hardened by cold-rolling, drawing, or forming are heated to some appropriate temperature close to, but below, the Ar_1 to relieve stress and to restore their initial ductility so that their fabrication may be continued. This is known as *process* annealing and is carried out at a temperature between 950 and 1300F. As pointed out later, cold-working causes distortion of the crystal lattice of metals and results in strain-hardening. By heating to a suitable recrystallizing temperature and cooling at a rate appropriate to the specific metal, this condition is removed. While carbon and low-alloy steels are invariably cooled slowly for annealing, the austenitic stainless steels are best annealed by quenching in water from about 2100F. Copper and aluminum may also be quenched in water from their respective annealing temperature. Car-type annealing furnaces are shown in Fig. 10–4.

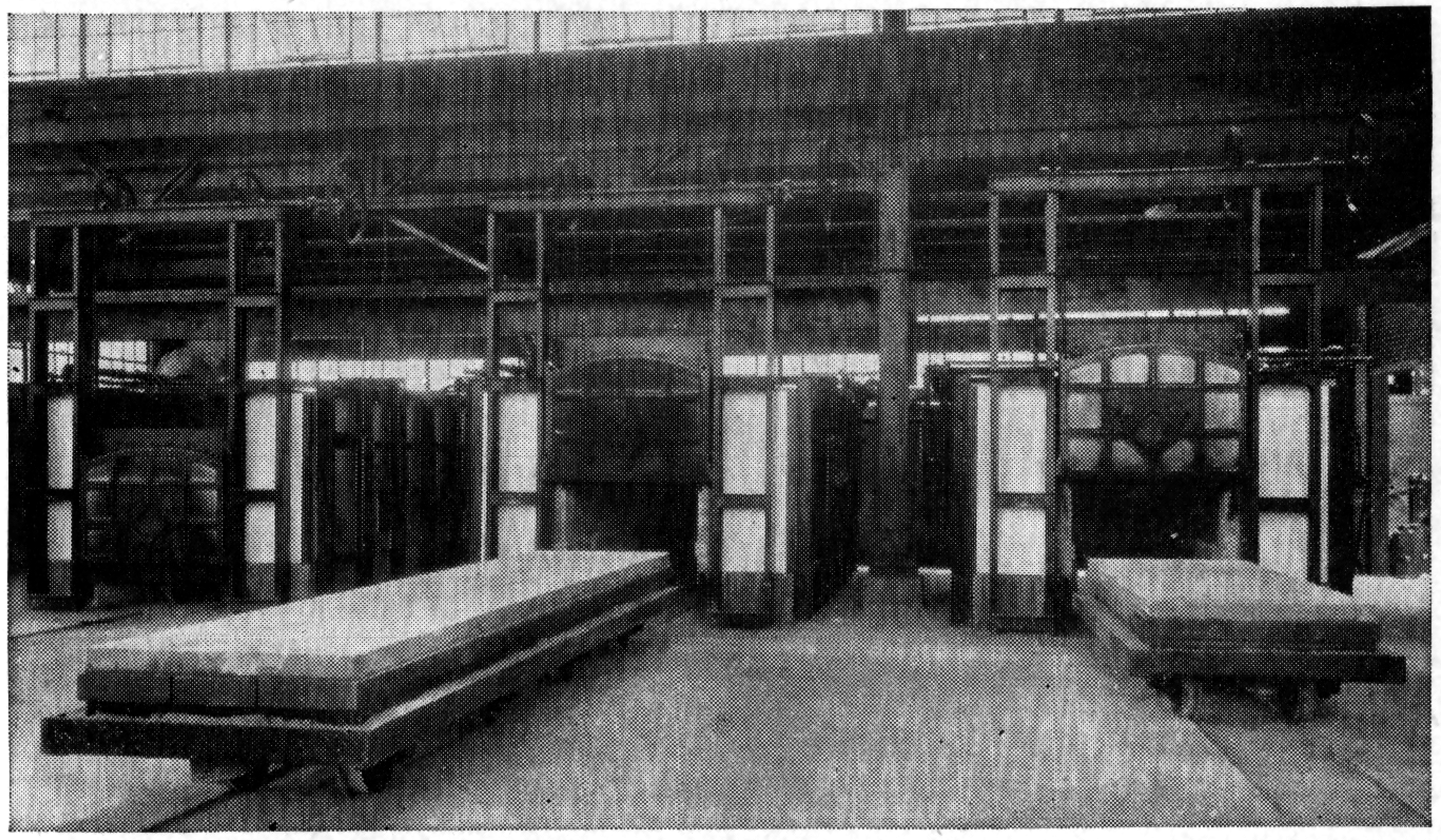


FIG. 10–4. Car-type annealing furnaces. Gas-fired. (Courtesy of George J. Hagan Company, Pittsburgh, Pa.)

Carbon steel wire of tool steel composition subjected to cold-drawing is heated to temperatures 200 to 300F above the critical to anneal and, purposely, to produce grain growth. This is followed by a cooling at a rate which will result in an emulsified pearlitic structure. The appropriate cooling rate may be obtained by cooling in air or in hot lead held at a temperature of 900 to 1150F; the latter is more frequently used when the composition of the steel is such that an air cool might result in increasing the hardness. This form of annealing is called *patenting* and is widely practiced in connection with wire drawing operations. Heating of high-pressure tanks, boilers, and other low-carbon steel weldments to about 1150F to relieve internal stresses is also a form of annealing, although no structural change takes place at this subcritical temperature.

10–3. Normalizing. The operation known as normalizing consists of cooling the steel in still air at ordinary temperature from about 100F above the Ac_3. Since the austenite transformation is slightly lowered by the faster cooling, the structure of normalized hypoeutectoid steel consists of well-distributed pearlite in the ferrite matrix and constitutes what is commonly referred to as an emulsified mass. And, as stated above, the air cooling between the Acm and Ar_1 prevents complete precipitation of the carbide in hypereutectoid steels as a continuous network.

The tensile and yield strength and ductility produced by normalizing are intermediate between those obtained by annealing and by a liquid quench.

The ductility of normalized high-carbon and alloy steels may be improved by a reheat to a temperature below the Ac_1 to temper or draw. And, for some alloy steel castings and forgings, this method alone produces satisfactory properties, especially where the sections are either large or complex and where cracking or warping might result from a liquid quench. It is generally thought inadvisable to quench parts having sections greater than 10 in., because nonuniform cooling rates give rise to internal stresses.

In order to homogenize or produce a structure more responsive to subsequent heat treatment, large forgings and castings are given a double normalizing treatment, which is followed by a third reheat to draw or temper. The first heating is carried out at a higher temperature than usual for a single normalizing. This is followed by an air cooling. After reaching a temperature approaching normal, the large forgings or castings are reheated to just above the Ac_3 and again cooled in air. They are later reheated to some appropriate temperature below the Ac_1, depending on the properties desired, and again air cooled. This treatment is calculated to produce excellent mechanical properties as well as a greater dimensional stability at elevated operating temperatures.

Hypoeutectoid and eutectoid steels are usually normalized to obtain end products such as desirable tensile strength, impact resistance, and release of internal stresses following hot-forging or a previous heat treatment, and to obtain refinement of the ferrite grains.

For hypereutectoid steels the process is generally used to condition them for subsequent heat treatments.

The microstructure of a normalized low-carbon steel is shown in Fig. 10–5.

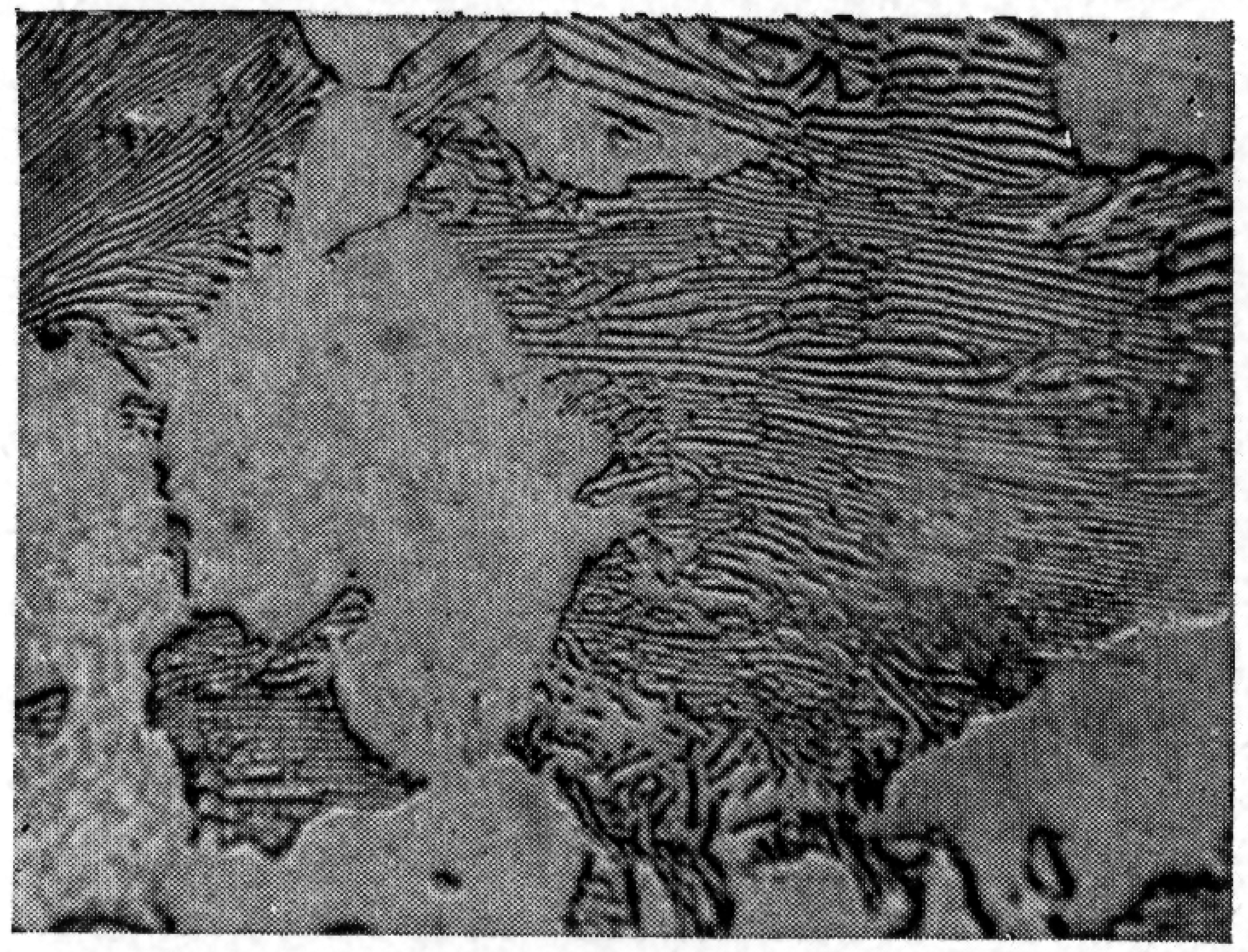


FIG. 10–5. Normalized structure of 0.54 per cent carbon steel showing pearlite and ferrite. ×1000. (Courtesy of School of Mines and Metallurgy, University of Minnesota.)

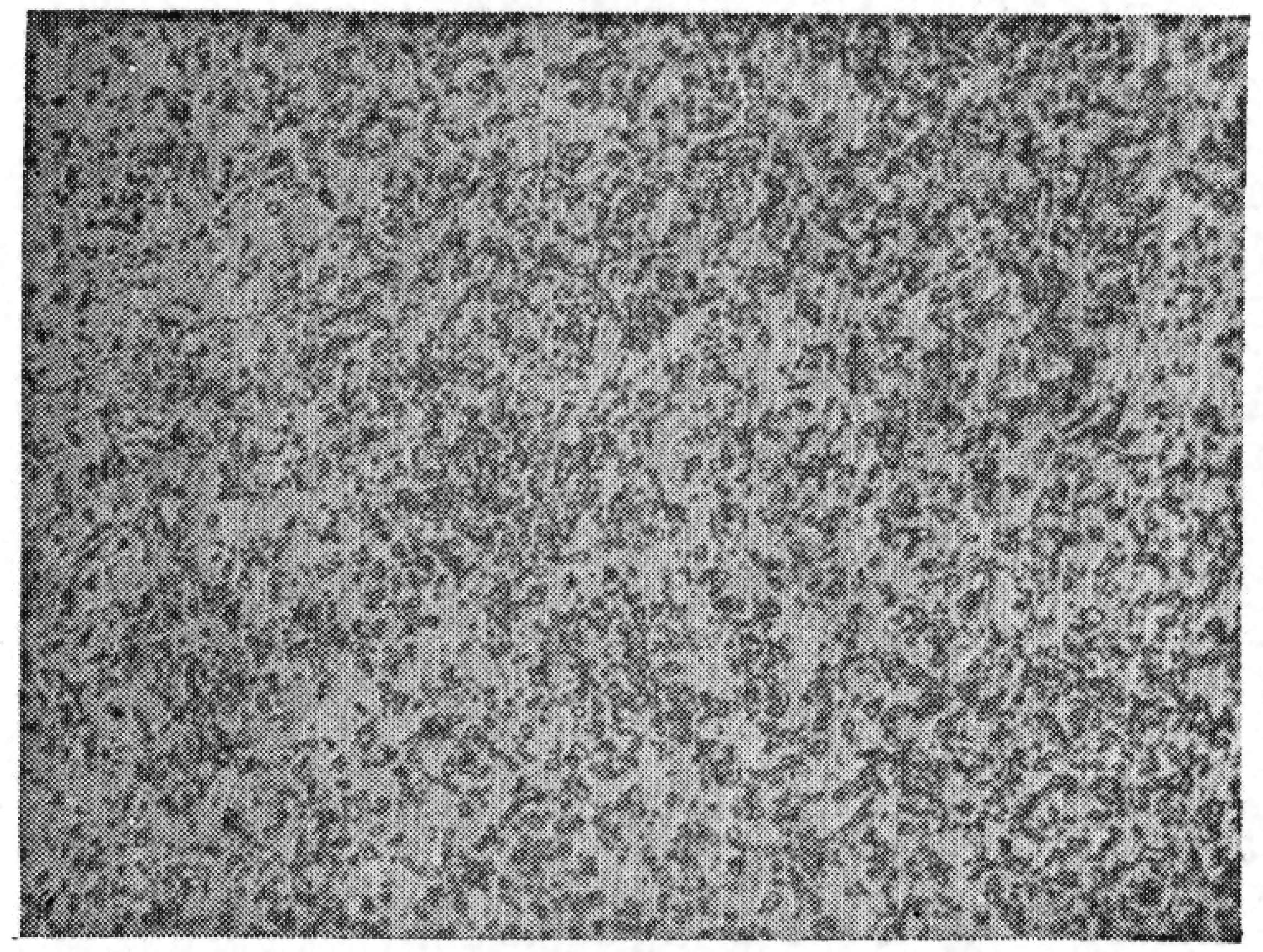


FIG. 10–6. Spheroidized pearlite of 0.86 per cent carbon steel. Quenched from above Ac_3 and tempered at 1300F for 10 hr. ×1000. (Courtesy of School of Mines and Metallurgy, University of Minnesota.)

10–4. Spheroidizing. As pointed out, variations in the cooling of fully homogenized austenite quite profoundly affect both the degree of its decomposition and the form of the constituents. Under certain conditions of temperature and time, the carbides influenced by surface tension will assume a form in which they possess the lowest ratio of surface to volume, i.e., they become spherical. When the carbides exist in this form, the structure is called spheroidal pearlite and is shown in Fig. 10–6.

This structure renders the steel more susceptible to uniform hardening and is preferred to an annealed or normalized structure for certain machining operations. Spheroidizing of lamellar pearlite is governed by the initial fineness or coarseness of the structure. Fine lamellar pearlite becomes spheroidized by heating just below the Ac_1 for a relatively short time, while large and coarse aggregates of pearlite require heating to between the Ac_3 and Ac_1 for a longer period, depending on the structure, followed by a reheat to below the Ac_1. A long-time draw or tempering of martensite at a temperature just below the Ac_1 also causes the carbide to coalesce as spheroids. A rapid method for the spheroidization of high-carbon steels consists of heating to slightly (25 to 50F) above Ac_1 for ½ hr, cooling to slightly (25 to 50F) under Ac_1, and holding for 2 to 6 hr for isothermal transformation. Holding time at temperatures is of paramount importance to avoid excessive coalescence of the carbides, which retards their dissolution rate and may cause nonuniform hardening.

10–5. Hardening. While the heating phase is similar for either hardening or annealing and produces similar structural changes, yet the results of hardening and annealing on the mechanical properties of steels containing sufficient carbon are vastly different. These differences in properties result from the subsequent relative cooling rate.

Hardening is defined as heating and quenching certain iron-base alloys from a temperature either within or above the critical temperature range for the purpose of producing a hardness superior to that obtained when the alloy is not quenched.

10–6. Mechanism of Hardening. The increase in the hardness of a steel cooled rapidly from the proper temperature corresponds to the lowering of the austenitic transformation. As shown in Fig. 10–7, with a slow cooling rate, the transition takes place at the eutectoid (Ar_1) temperature, when coarse lamellar pearlite is formed. Faster cooling will cause the transformation to take place at a lower or subcritical temperature designated Ar', or between 1100 and 850F. When the transformation takes place in this range, the structure represents the optimum degree of fineness of lamellar pearlite. It is called primary troostite. Because of the very close spacing of the lamella, it is sometimes referred to as an emulsion of carbides. While it is difficult to resolve under the microscope, it has been proved by means of high magnifications that the structure is a very fine lamellar pearlite. Primary troostite combines moderate hardness and tensile strength with considerable toughness.

With very fast cooling rates, such as those obtained when small parts are cooled in cold water or brine, the Ar' reaction decreases in intensity; and, for high-carbon and low-alloy steels, it disappears altogether. Under these conditions, the austenite transforms at another and lower temperature, which is designated Ar''. Provided the cooling rate is sufficiently rapid, the austenite remains unchanged until a temperature of about 400F or lower is reached, when it transforms directly into acicular martensite.

With a cooling rate intermediate between a fast and a very fast rate, a partial transformation will take place at the Ar', with the residual austenite transforming at the Ar''. The resultant structure of a dual transformation would consist of both primary troostite and martensite.

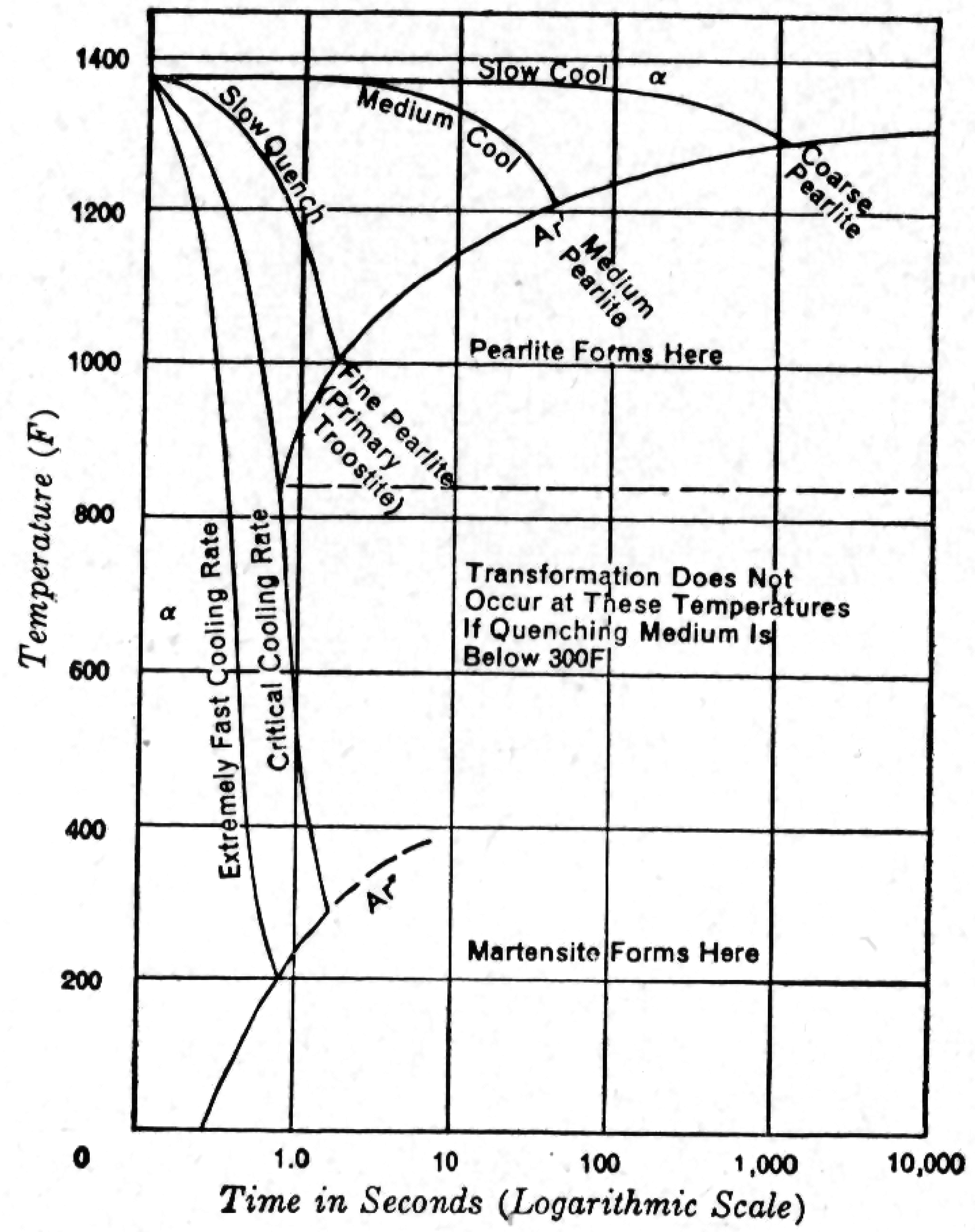


FIG. 10–7. Schematic representation of time and temperature of initial transformation of a eutectoid steel as cooled at various temperatures. (Adapted from *Engineering Physical Metallurgy* by Robert H. Heyer, D. Van Nostrand Inc., New York.)

Some favor the theory that *carbide* is precipitated from the austenite at the Ar''; however, the more widely accepted theory is that martensite is a supersaturated solid solution of *carbon* in alpha ferrite. Martensite is the hardest structure of steel. By means of the X-rays, it is shown to have a tetragonal, rather than a cubical, crystal structure. After the martensite has been etched with picric or nitric acid, the microscope reveals its characteristic needlelike, or acicular, structure with no visible grain boundaries. Pure martensite possesses an extremely high tensile strength and practically no ductility. Its hardness varies with the carbon content from about 40 Rockwell C for a low-carbon steel to almost 70 Rockwell C for eutectoid and hypereutectoid steels. The microstructures of troostite and martensite are shown in Figs. 10–8 and 10–9. The density of martensite is slightly less than that of the same steel in the annealed state. The gamma-alpha transition, which involves only a shift in the atomic arrangement from the face-centered to the body-centered cubic system, takes place almost completely during the rapid cooling of a plain carbon steel; and, therefore, except for an insignificant amount, the austenite transforms completely into martensite at the Ar''.

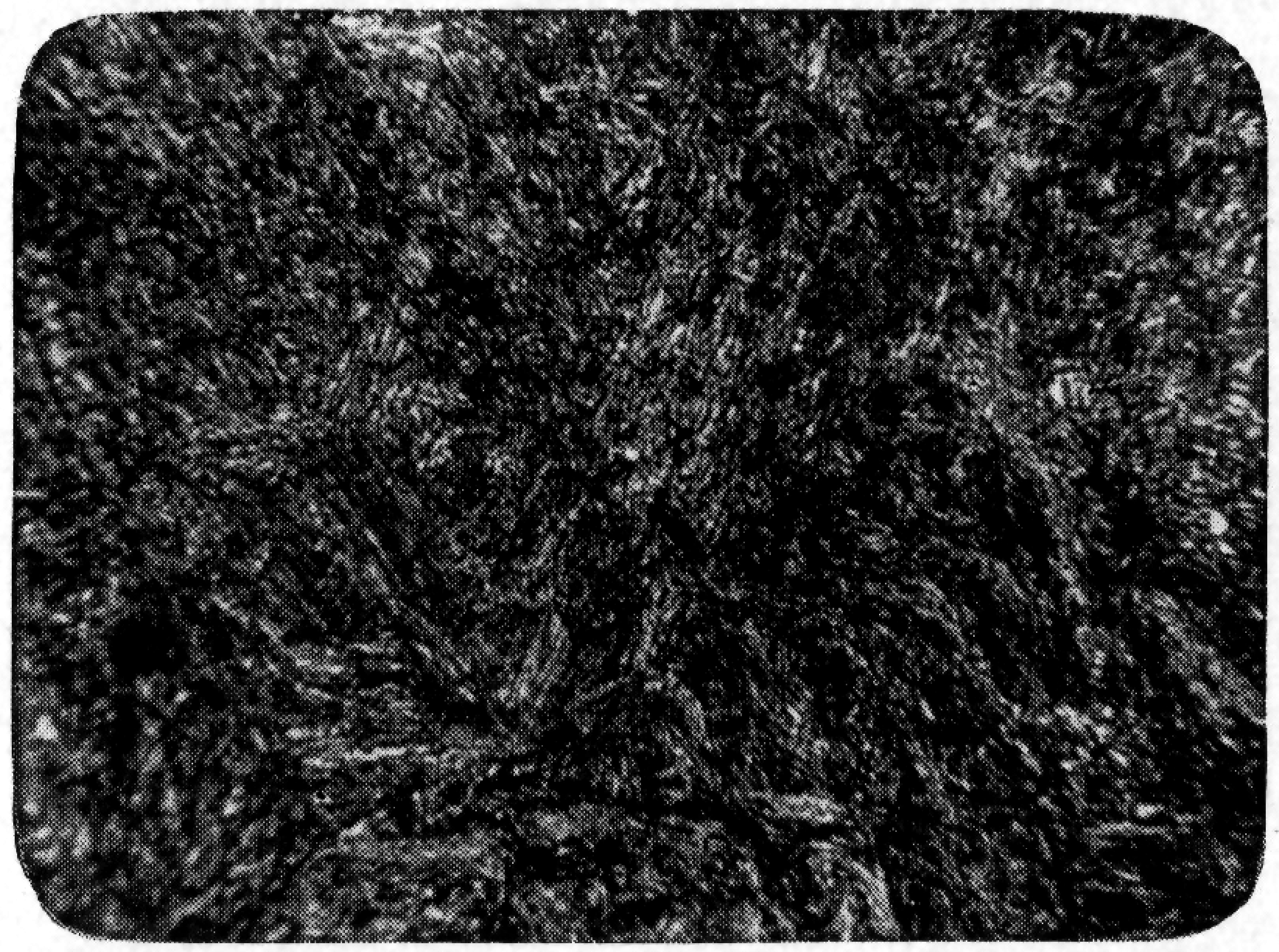


FIG. 10–8. Photomicrograph of troostite with 0.90 per cent C quenched from above Ac_3 and tempered at 800F for 1 hr. ×1000. (Courtesy of the School of Mines and Metallurgy. University of Minnesota.)

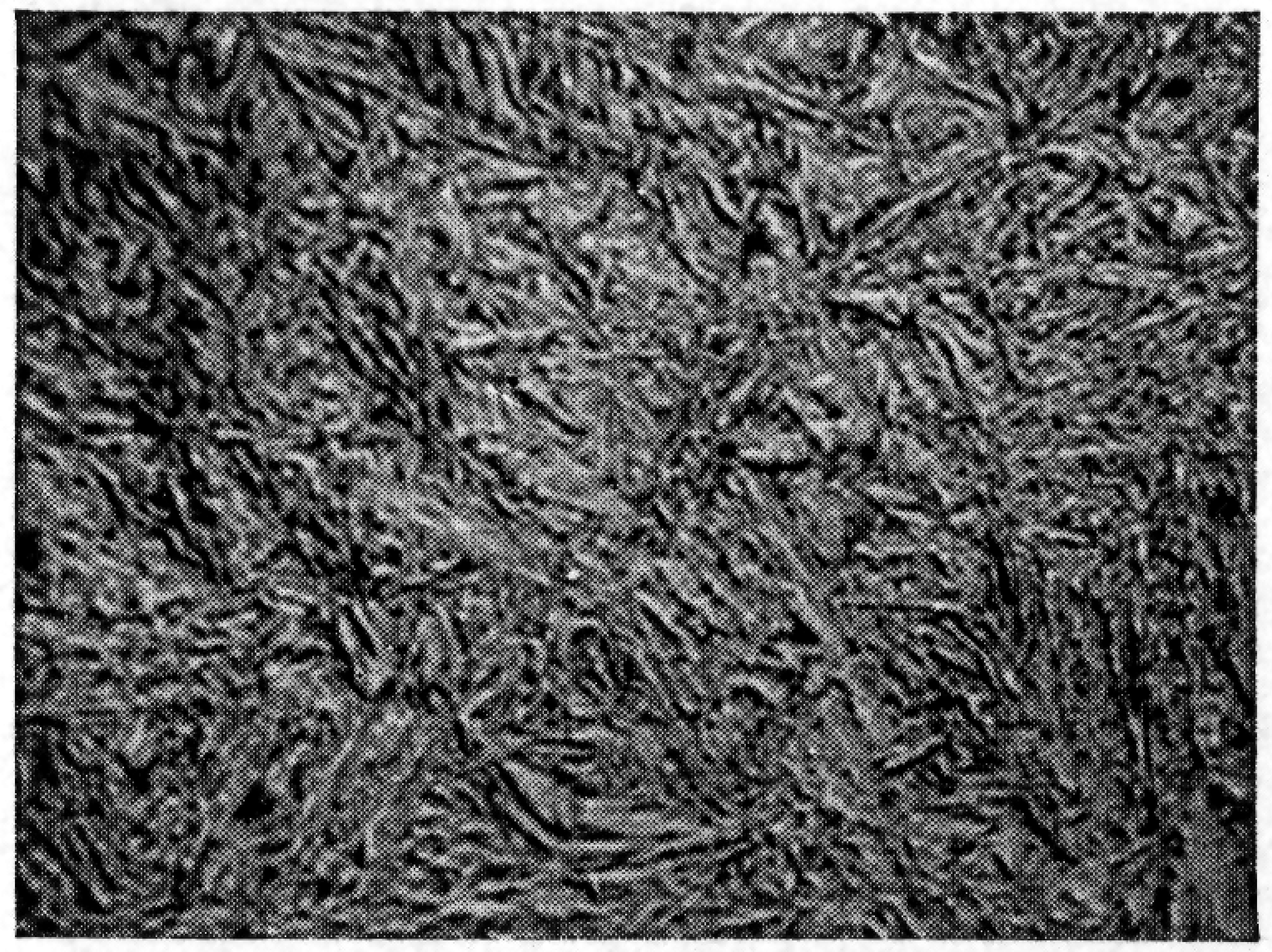


FIG. 10–9. Martensitic structure of 0.90 per cent carbon steel. Quenched in water from above the Ac_3. ×1000. (Courtesy of School of Mines and Metallurgy, University of Minnesota.)

The fundamental reasons most universally given for the hardness of martensite are (1) that it is a supersaturated solid solution, (2) that it is a highly stressed structure, and (3) that the lattice is distorted. These

factors are closely interrelated and involved, and their study should be pursued in more advanced texts. The influence of carbon on the maximum hardness of steels is shown in Fig. 10–10.

10–7. Practical Aspects of Hardening. The principal requirements for increasing the hardness of steels by heat treatment are (1) that they be heated to some temperature to obtain either complete or a desired degree of homogeneity of the constituents, (2) that the cooling rate be rapid, particularly through the critical range, to prevent the austenite-pearlite transition, (3) that the austenite transform entirely to martensite, and (4) that the steel contain sufficient carbon. No appreciable increase in hardness is obtained by quenching plain carbon steel containing much below 0.30 per cent carbon.

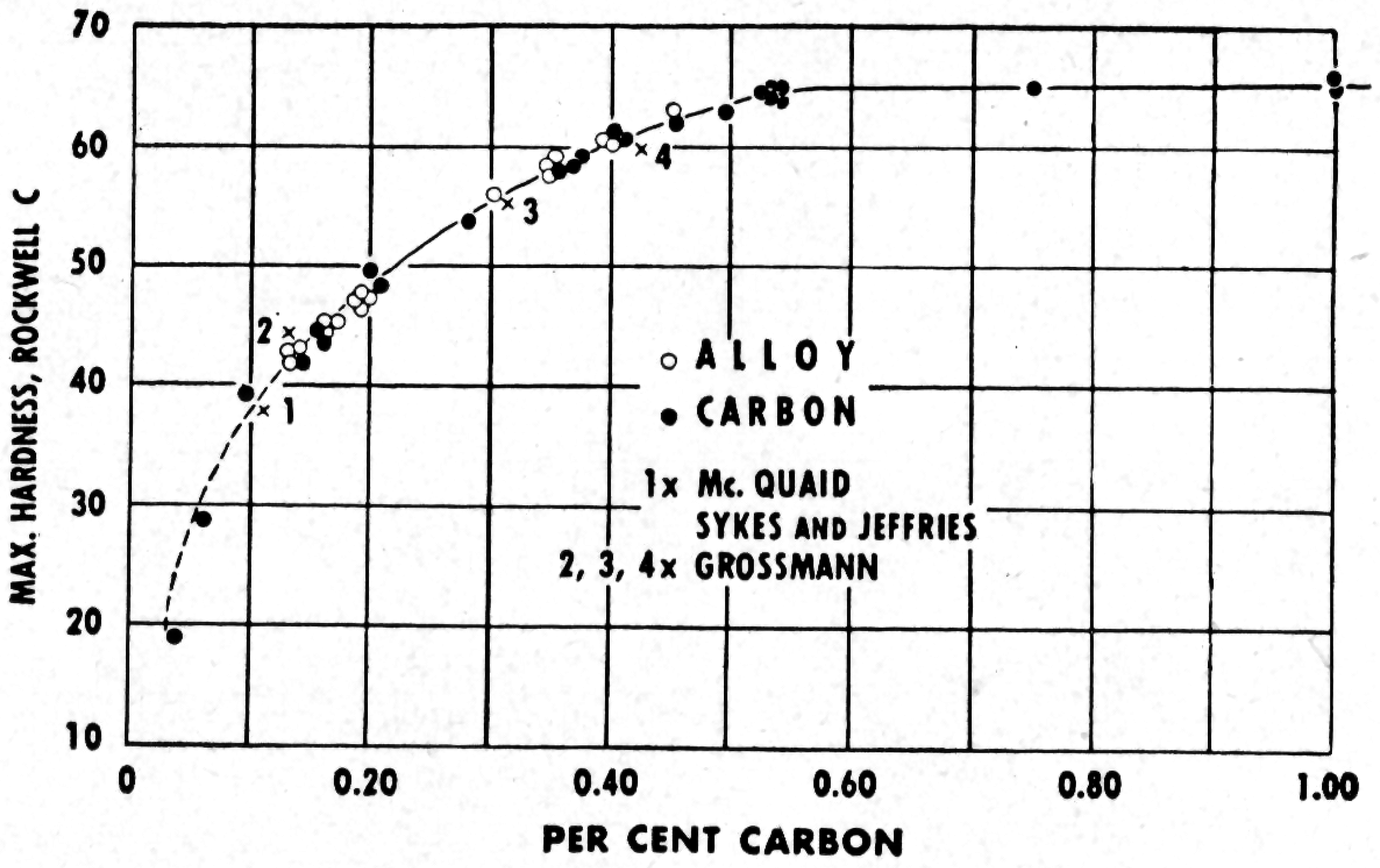


FIG. 10–10. Maximum hardness versus carbon content.

10–8. Heating Cycle. This phase of the hardening process is one of the most important, since it requires consideration of the rate of heat application to the object. The metal, heated by radiation and conduction, absorbs heat at its surface until it has attained the temperature surrounding it. Other parts below the surface become heated by conduction of heat through the surface exposed to the heating medium. To avoid wide temperature gradients within the object, the heat input, therefore, must be conditioned by (1) the ratio of the surface area of the part to its mass, (2) its size, (3) its analysis, (4) previous condition or structure, and (5) specific properties of the metal. Generally, a heating interval of from ½ to 1 hr per in. of maximum diameter or thickness suffices, depending on the alloy.

As a general rule, it may be assumed that steels exhibit endothermic and exothermic reactions when heated and cooled through the critical temperatures and that these are accompanied by a slight contraction and dilation, respectively. If sufficient time is not allowed for uniform heating, these endothermic reactions will cause volume changes to take place in various zones or sections of the steel at different times, thus producing possible internal stresses, distortion, or cracking. Provided that uniform temperature of the object has been maintained during the heating phase, the time of holding for complete homogenization at the quenching temperature can be reduced to a minimum.

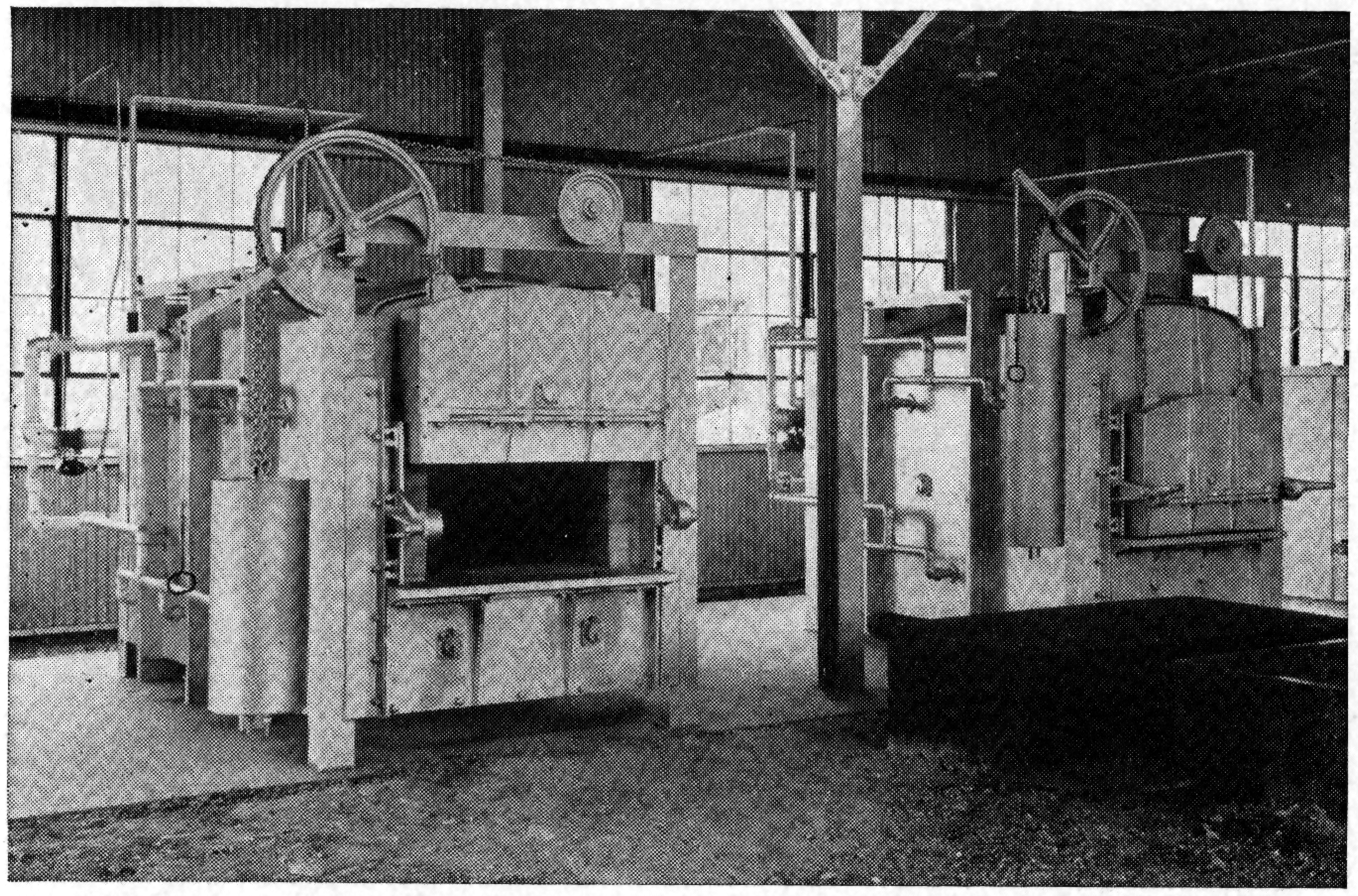


Fig. 10–11. Two typical batch type heat-treating furnaces, gas-fired. (Courtesy of Mahr Furnace Co., Minneapolis, Minn.)

10–9. Heating Methods. Commercial heating for heat-treating of metals is carried out in various types of furnaces which utilize gases, oils, or powdered coal as fuel. Many furnaces are also heated by electrical resistance. Generally, these furnaces are equipped with both temperature and atmosphere controls to assure uniform temperature and to minimize oxidation. Production practices are carried on in batch and continuous operating types. Batch furnaces shown in Fig. 10–11 are loaded and unloaded through a door or top cover and are designed with either horizontal hearths or vertical pits. The latter are generally used for heating large guns and similar long objects which are suspended vertically; they are also adapted for heating a large number of small parts contained in a steel basket or suitable fixture, as shown in Fig. 10–12. The parts may also be supported individually in these containers to insure uniform heating and to prevent warpage. Continuous operating furnaces are loaded at one end and the parts are moved slowly through the furnace, attaining the proper temperature before being removed at the quenching end.

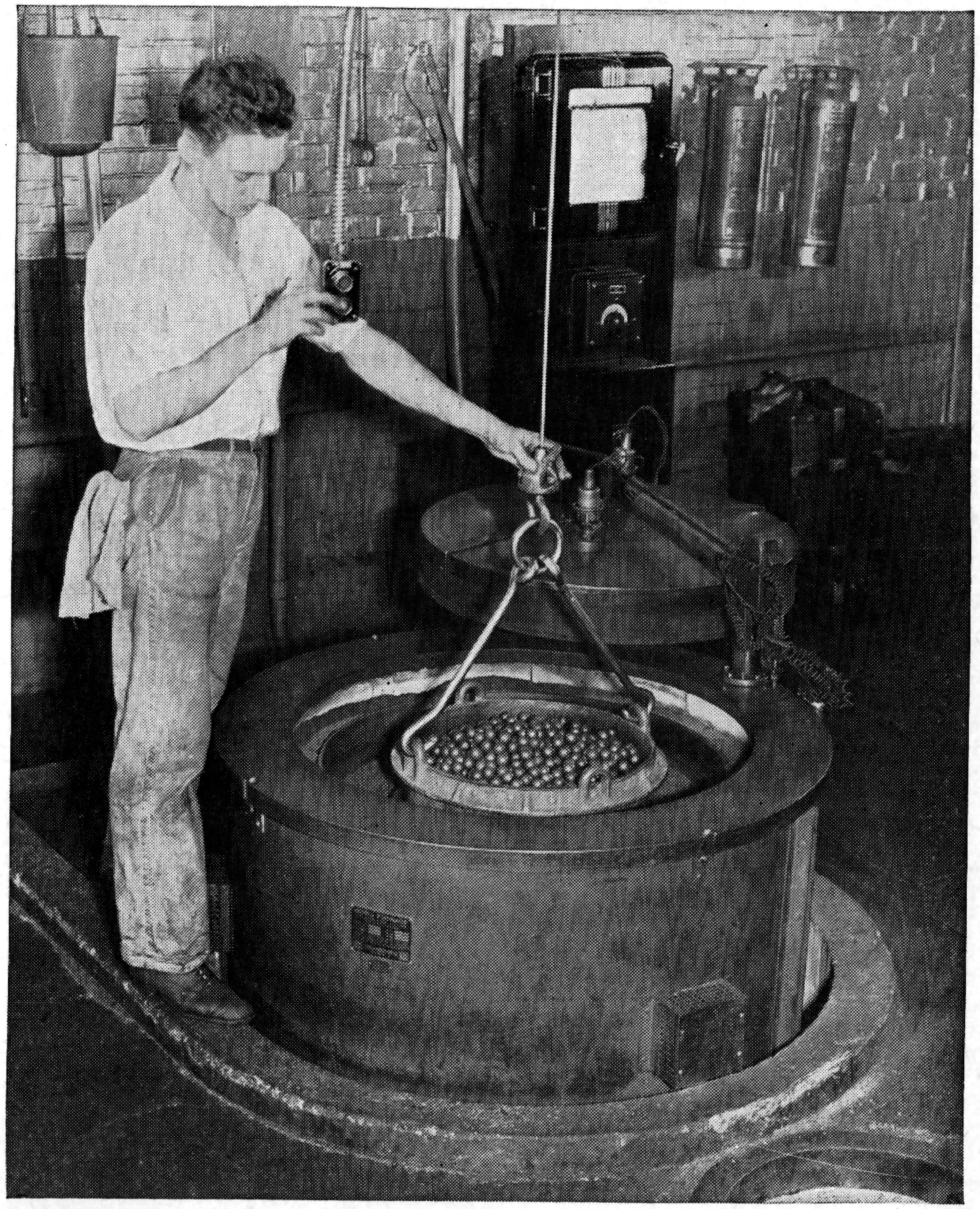


Fig. 10–12. Lowering a load of ball bearings into an electric furnace whose temperature is automatically controlled and recorded by panel instrument on wall. (Courtesy of Leeds and Northrup Company.)

Rapid and localized or surface heating may be obtained either by high-frequency induction current or by an adaptation of the oxyacetylene torch. (Examples of induction heated parts are shown in Figs. 10–28 and 10–29.) Certain parts such as dies, punches, gauges, and sharp edged tools are frequently heated in fused solution of salts or in molten metals to prevent oxidation and to obtain uniform heating. These should first be preheated by other means.

10–10. Temperature. The temperature that the steel reaches is significant because underheating results in only a partial hardness while overheating, except in the inherently fine-grained steels, produces a large austenitic grain size. The highest temperature should be that at which the phases are completely soluble and the austenite is wholly homogeneous. This condition, when followed by a suitable cooling rate, will result in the steel possessing the maximum hardness.

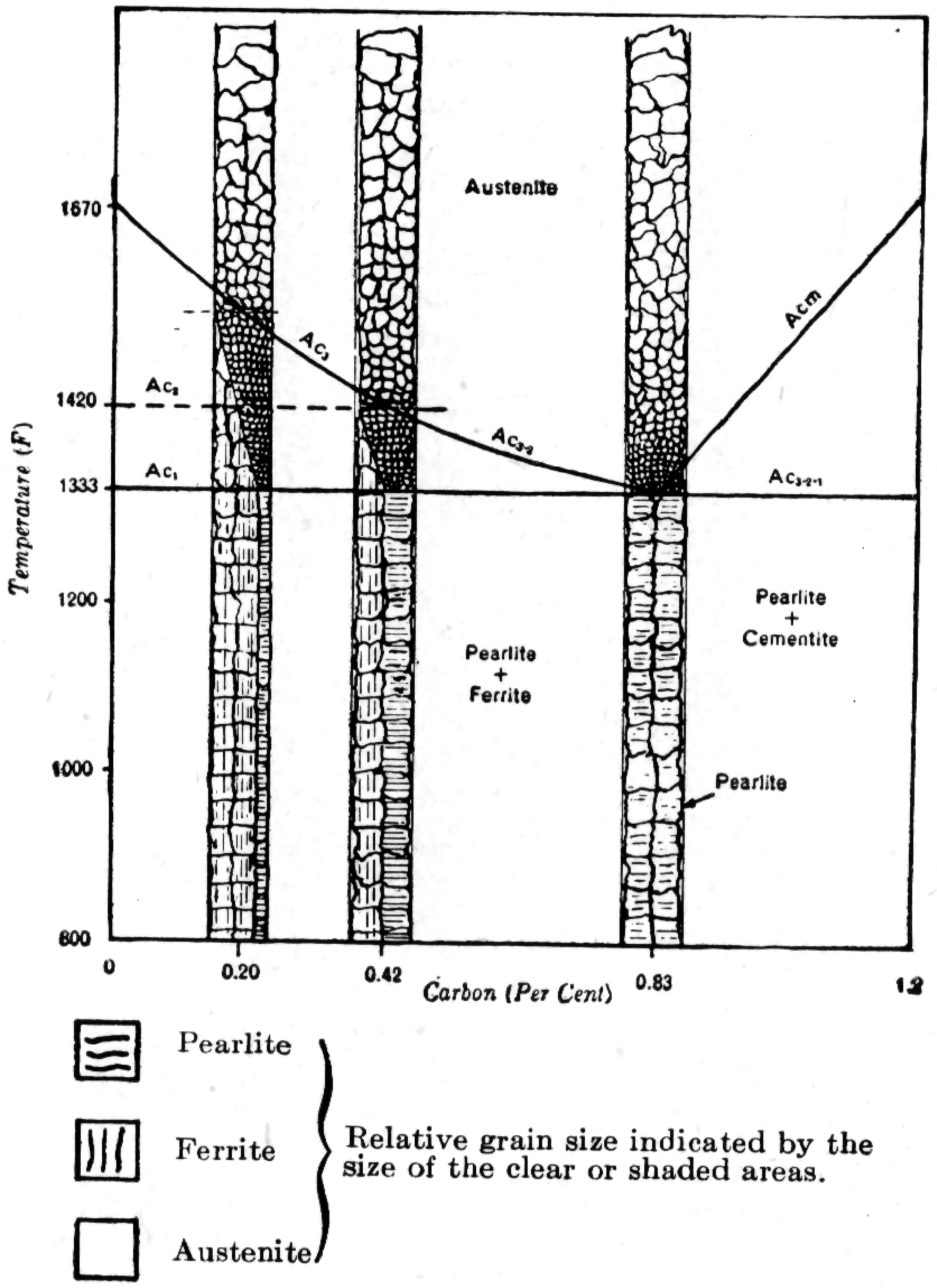
As no change in the microconstituents, ferrite and pearlite, takes place below the Ac_1, quenching from any temperature below this range produces no results. Heating hypoeutectoid steel to some temperature between the Ac_1 and Ac_3 and cooling rapidly produces a hardness in proportion to the amount of ferrite soluble in the austenite at that temperature level. The free ferrite will remain unaffected. With progressively higher temperatures, but below the Ac_3, liquid cooling will result in correspondingly higher hardness but still below the maximum potential hardness of the steel. The best combination of hardness and strength is therefore obtained by quenching hypo- and eutectoid steels from just *above* the Ac_3. Changes on heating these steels are shown diagrammatically in Fig. 10–13. Hypereutectoid steels are quenched from a temperature between the Ac_1 and Acm. As shown on the diagram Fig. 9–6, the Acm rises steeply with increasing carbon and, to dissolve all free carbide in the austenite, it will be necessary to heat above the Acm temperature. It is customary, however, to heat to some lower temperature or between the Ac_1 and Acm and retain some undissolved but well-distributed carbide so as to avoid grain coarsening tendencies and subsequent cracking of the parts when quenched.

10–11. Cooling. It is immaterial whether certain single-phase metals and alloys are cooled from elevated temperatures slowly or rapidly, because heating produces no structural or phase changes. However, the cooling rate of metals and alloys which undergo phase changes determines their constitution and properties at normal temperatures.

Quenching is the immersion of hot steel in a liquid medium for the purpose of abstracting heat and cooling the steel at a rate which will bring about the desired results. Among the variables which must be considered in order to attain proper objectives are: mass, ratio of surface to volume or mass, temperature, specific properties, and motion of the steel during the quench; also, the temperature of the coolant, its viscosity, volume, and specific heat, and the velocity of its motion.

The most commonly used coolants for quenching plain carbon and low-alloy steels are various oils, water, and aqueous solutions of 10 per cent sodium chloride and 5 to 10 per cent sodium hydroxide.

The relative quenching powers of oil and water for various diameters are given in Table 10–2, and the effect of volume on the tensile properties of heat-treated steels is given in Table 10–3. These results were obtained with steel of the same analysis and heat-treated similarly in regard to quenching and drawing temperatures. They illustrate clearly the influence of the rate of cooling, as affected by volume, on the mechanical properties of the steels.



Below Ac_2 no change occurs in constituents or grain size.
At Ac_2 all the pearlite transforms to austenite.
Between Ac_2 and Ac_3 the solution of ferrite in austenite proceeds gradually, the ferrite remaining unaffected until dissolved.
Above Ac_3 the alpha-gamma transformation is complete; the structure is entirely austenitic.
Eutectoid steel transforms completely at $Ac_{1\text{-}2\text{-}3}$.

FIG. 10–13. Transformation during the heating of hypoeutectoid and eutectoid steels.

No definite procedure can be given for the quenching of steels, because practices must be adapted to the shape, size, analysis, and subsequent use to be made of the parts. Common difficulties encountered are cracking, warping, and nonuniform hardening. Special techniques and devices are often necessary to minimize warpage and to correct it quickly when it has occurred. Short shafts may be rolled in and out of quenching baths. Large and long shafts and gun barrels are lowered vertically into deep tanks or wells of oil. Tools, such as master gauges, dies, etc., are usually made of alloy oil-hardening steels to avoid dimensional changes during the cooling. Other parts, such as gears, are held in special fixtures or machines during quenching to prevent warpage.

TABLE 10–2

COMPARATIVE HARDNESS AT SURFACE OF WATER- AND OIL-QUENCHED SAE 1045 STEEL*

DIAMETER OF PIECE	HARDNESS	
	Water	Oil
0.5	59	29
1.0	58	29
2.0	41	28
3.0	35	23
4.0	30	23
5.0	24	18

*Grossman, M. A., *Principles of Heat Treatment.*

TABLE 10–3

EFFECT OF VOLUME ON RESULTS OF HEAT TREATMENT*

Rod Size (In.)	Tensile Strength (Psi)	Elastic Limit (Psi)	Elongation (Per Cent in 2 In.)	Reduction of Area (Per Cent)
1	138,500	106,000	18.80	60
2	125,000	95,000	19.00	58
3	112,000	84,000	19.50	56
4	107,000	70,000	19.00	54
5	105,000	69,000	18.90	54
6	98,000	68,500	19.00	49

*Van Dyke, Ryerson Steel Company.

The austenite transformation to martensite is accompanied by a slight volume increase when plain carbon and low-alloy steels are cooled rapidly. Fig. 10–14 shows the result obtained by cooling one half of the width of a thin plate in water while the other half cooled in air.

Quenching cracks are caused by high internal stresses accentuated by sharp corners, re-entrant angles, lack of proper balance between component parts, and such improper techniques or practices as quenching from too high a temperature or failing to properly relieve the stresses by tempering, as described in the following material. Previous structure

or condition of the steel, such as normalized or annealed, is also an important factor.

Nonuniform hardening is promoted when a heavy surface scale (caused by heating in an oxidizing atmosphere) breaks off, exposing some areas to the coolant while retarding the cooling of other areas to which it still adheres. Because the drastic cooling action of water, brine, or solutions of caustic soda usually causes the scale to break off upon contact with the coolant, soft spots on hardened parts thus quenched are not as common as on parts cooled in oil. With the more moderate cooling action of the oil, the scale tends to cling. Vapors or gases, which collect in restricted pockets such as corners, also contribute to soft spots in that they keep the coolant away from those parts. Keeping the parts being cooled or the coolant in constant state of agitation during the cooling period will improve this condition.

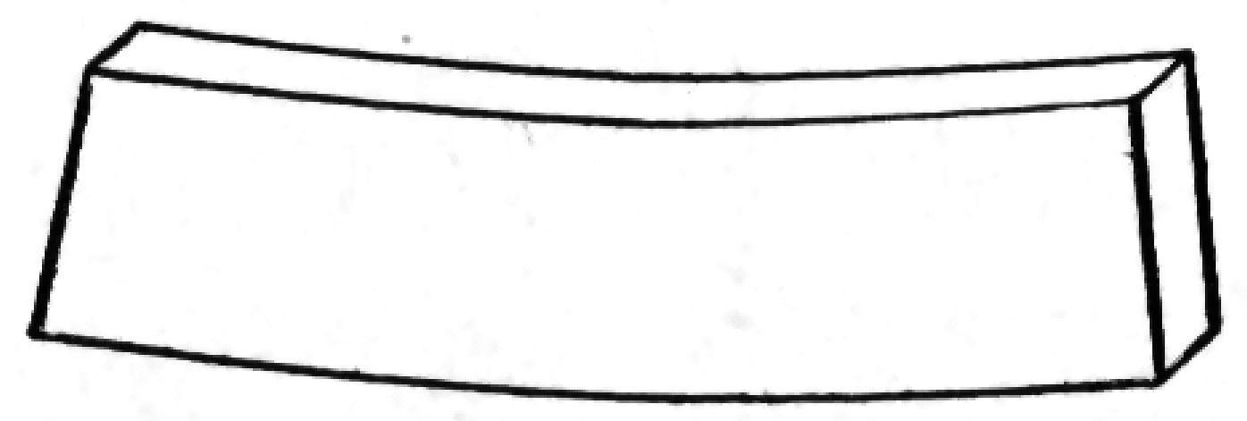
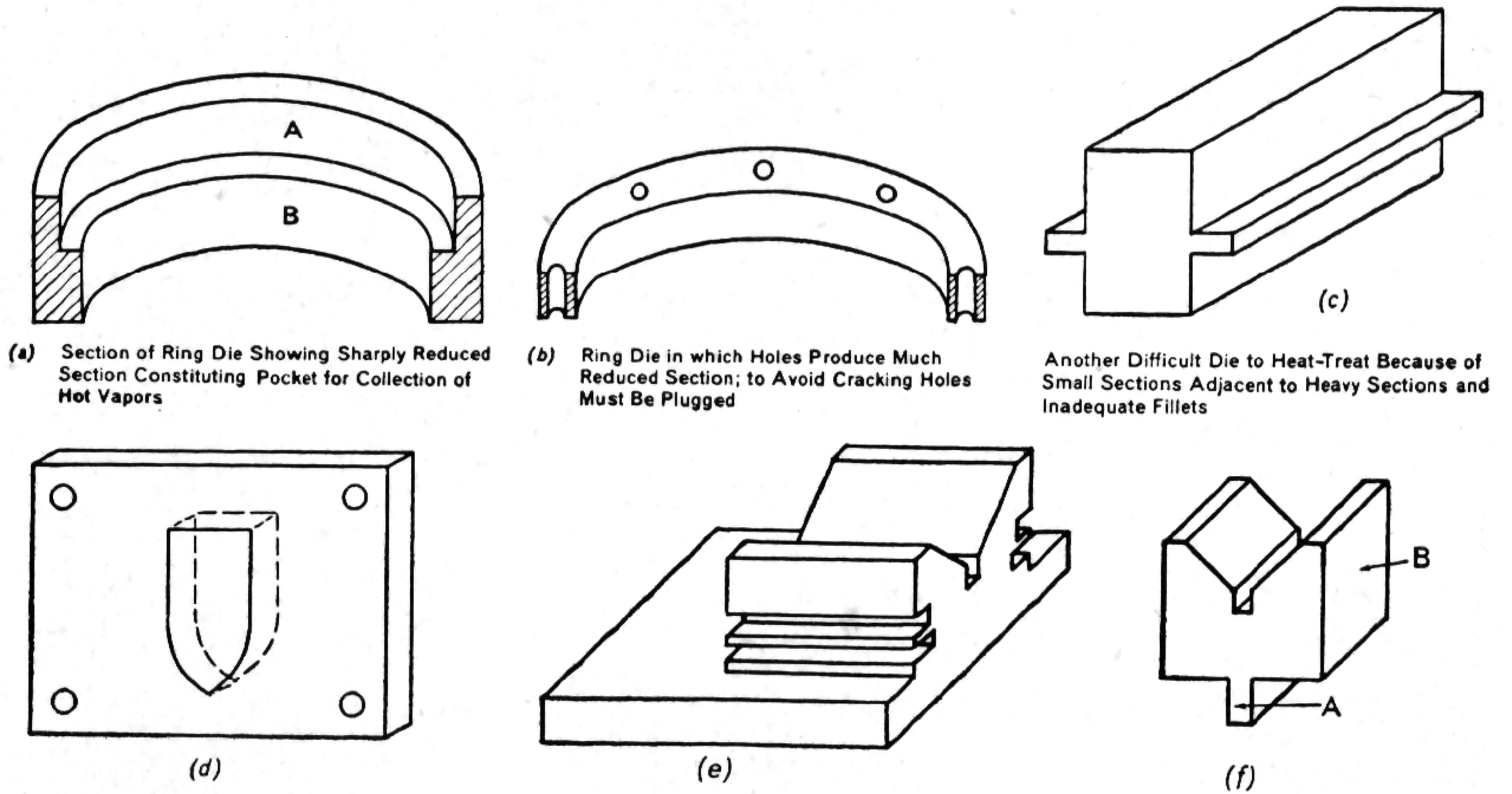


FIG. 10–14. Distortion produced in plate containing 0.80 per cent C by cooling lower half in water and upper half in air.



(a) Section of Ring Die Showing Sharply Reduced Section Constituting Pocket for Collection of Hot Vapors

(b) Ring Die in which Holes Produce Much Reduced Section; to Avoid Cracking Holes Must Be Plugged

(c) Another Difficult Die to Heat-Treat Because of Small Sections Adjacent to Heavy Sections and Inadequate Fillets

(d) Sharp Point at Profile of This Die May Act as Stress Raiser and Cause Cracking

(e) Part with Unbalanced Sections and Provided with Inadequate Fillets in Corners

(f) Badly Unbalanced Die Which Makes Heat-Treating Difficult

FIG. 10–15. Parts requiring special care in heat-treating.

Machine parts, which unavoidably must consist of unequal sections and sharp corners, may be hardened by first quenching in water to obtain a rapid cooling rate past the Ar_1 and then finally cooling in air or oil. This suppresses the austenite transformation and thus permits the formation of martensite (see Fig. 10–7), while the subsequent slower cooling rate provides the steel an opportunity to adjust itself slightly during the period when cracks most frequently occur. Some parts may also be cooled completely by quenching in suitable baths of salts or metals. To prevent cracking, it is also necessary at times to prevent direct contact of critical sections with the coolant so as to obtain a slower cooling rate in those areas. Equalization of cooling throughout a part having unbalanced sections may also be obtained by plugging holes or cavities with asbestos rope or asbestos cotton prior to heating. Examples of parts which require special precautions in heat-treating are shown in Fig. 10–15.

10–12. Critical Cooling Rate. The cooling velocity required to cause the transformation of austenite to martensite at the Ar'' without any primary troostite is called the critical cooling rate. Since to abstract heat from a large body of metal uniformly from surface to center is almost physically impossible, the critical cooling rate cannot be maintained except on small or thin sections or to a variable depth below the surface of larger sections, as shown in Figs. 10–16, 17, and 18. These differential cooling rates within the part give rise to high internal stress, cause the transition of austenite to proceed in stages, and, consequently, produce hardnesses which decrease from the surface to the interior (as shown in Fig. 10–19). In order to obtain deeper hardening effect, a steel of low critical cooling requirements is desirable. And, while carbon is one of the most potent elements contributing toward a low critical cooling rate, the presence of alloying elements such as nickel and manganese is also an important factor.

The depth to which a steel hardens is termed its hardenability. And the deeper it hardens, the easier it is to heat-treat, because it may be cooled at a relatively slow rate. Since the hardenability varies inversely as the critical cooling rate, steels with a low critical cooling rate harden to a greater depth than those with a high cooling rate. Alloys lower the critical cooling rate, thereby making possible more uniform hardening of large sections and of smaller sections with less drastic quenches. This constitutes one of the most noteworthy contributions of alloy additions to steels. Independent of cooling rates, depth of hardness is also influenced by the initial austenitic grain size. Coarse grains tend to promote deeper hardening than small grains.

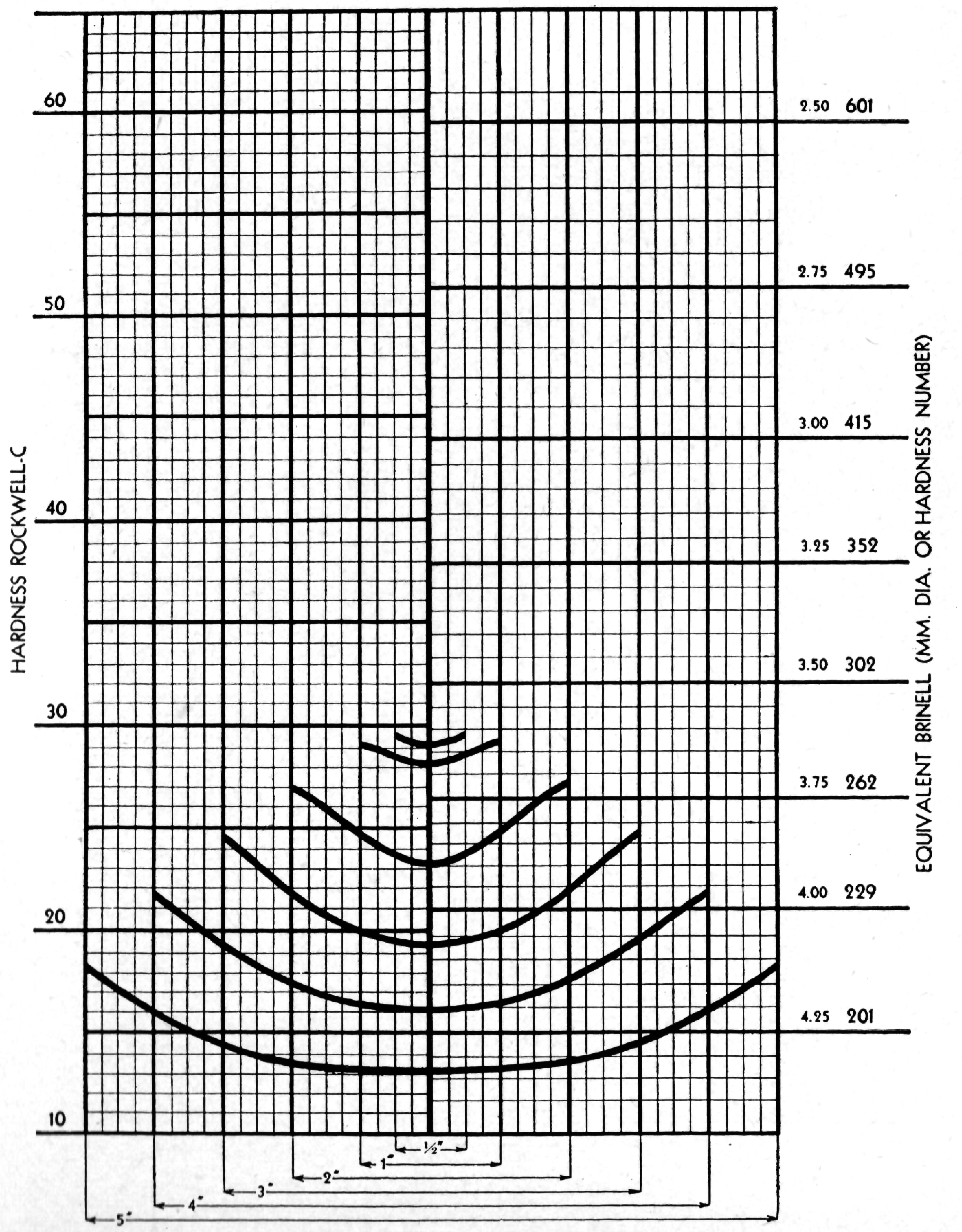


FIG. 10–16. Hardness distribution in various sizes of quenched round bars. SAE 1045 steel quenched in oil.

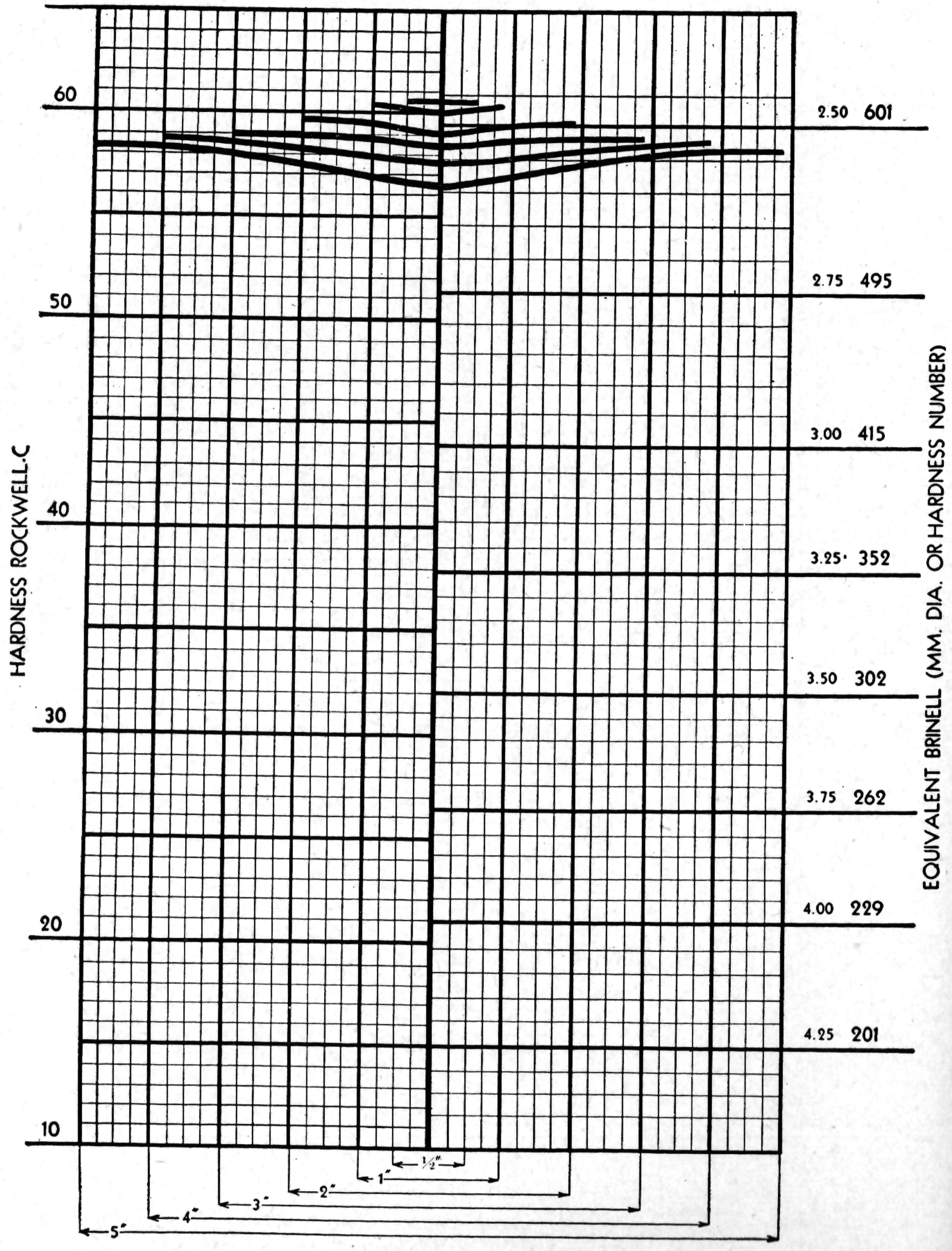


Fig. 10–17. Hardness distribution in various sizes of quenched round bars. SAE 3340 steel quenched in water.

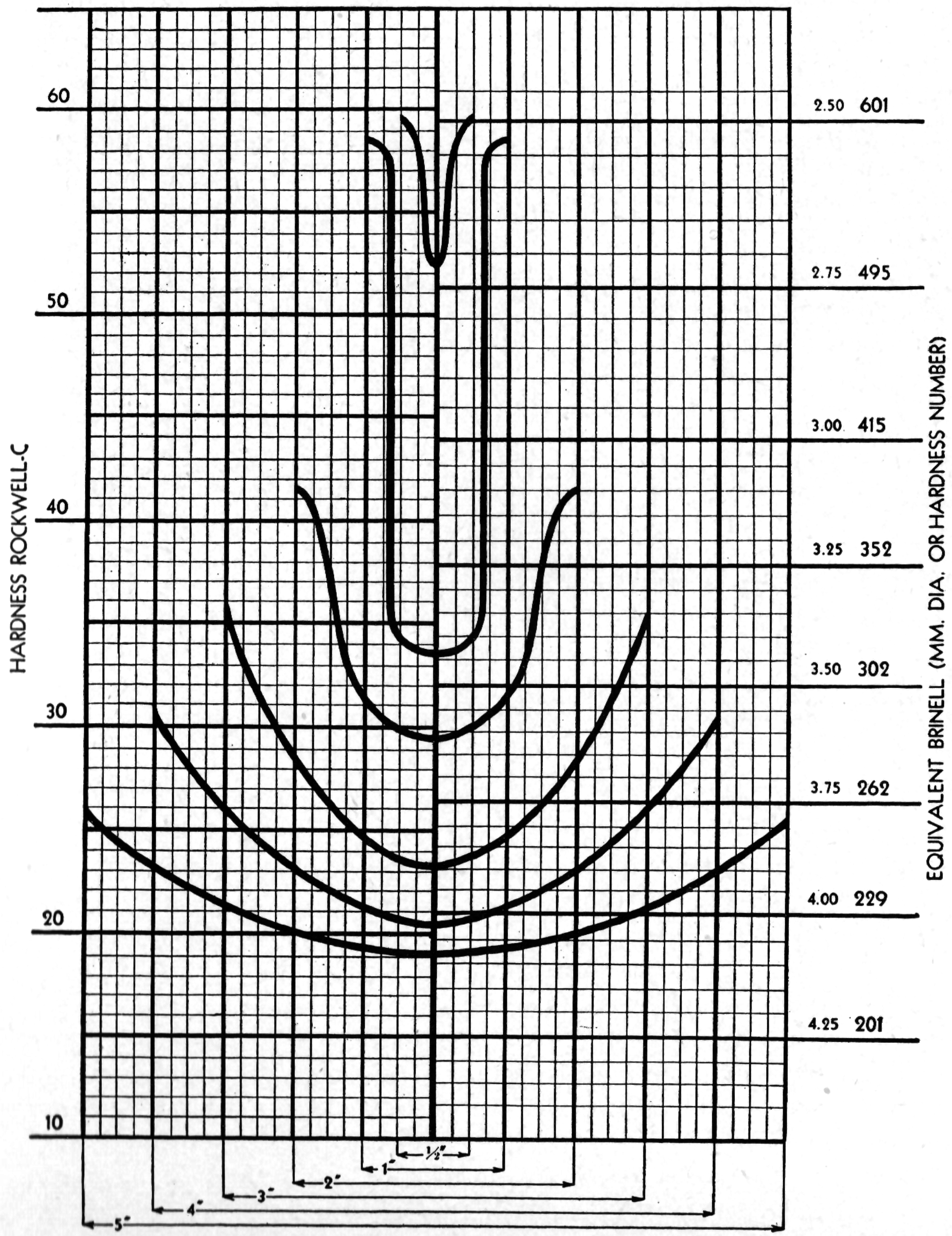


Fig. 10–18. Hardness distribution in various sizes of quenched round bars. SAE 1045 steel quenched in water.

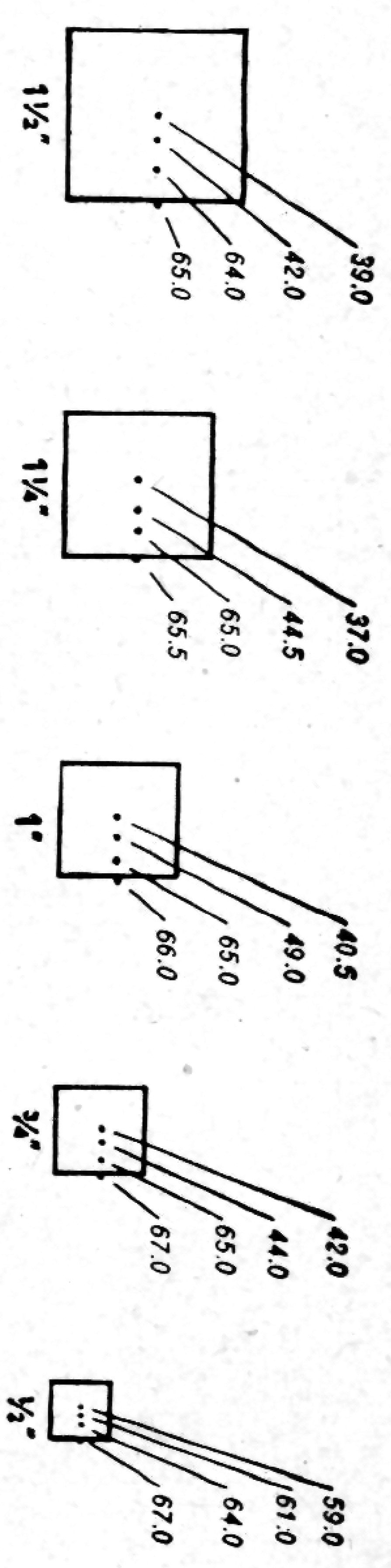


FIG. 10–19. Influence of section size on the Rockwell C hardness of a eutectoid steel quenched in water. Hardnesses were taken on ground surfaces after specimens were cut in half after hardening.

It is possible to estimate the approximate response of steels to hardening by assigning a value to each element present, other than iron. The values which may be used are as follows:

Element	Per Cent	Value	Element	Per Cent	Value	Element	Per Cent	Value
C......	0.01	30	Si.....	0.01	5	Mo....	0.01	16
Mn....	0.01	8	Ni.....	0.01	4	W.....	0.01	4
P......	0.001	4	Cr.....	0.01	5	Cu.....	0.01	4
S......	0.001	1	V......	0.01	20			

Provided that the steels are inherently similar as to quality, are of the same size, and are heated under identical conditions, their response to heat treatment may be predicted. Solubilities and detailed influences of various alloying elements are given in Table 10–4.

10–13. Tempering. The reheating of quench-hardened steels to some temperature below the critical is called tempering or drawing. Its purpose is to relieve internal stresses, increase the impact toughness, or modify the hardness. Because brittleness varies almost directly as the hardness, steels are very seldom put into service until they have been reheated to some desirable temperature for toughening.

Figs. 10–20A and 10–20B show the effect of tempering temperature upon the physical properties of a quenched steel. Tempering below 400F has a comparatively slight effect upon the hardness but may affect the toughness considerably, since the relief of quenching stresses is quite pronounced. Tempering above 400F causes a rather pronounced decrease in hardness and strength and an increase in the ductility, as measured by the elongation and reduction in area.

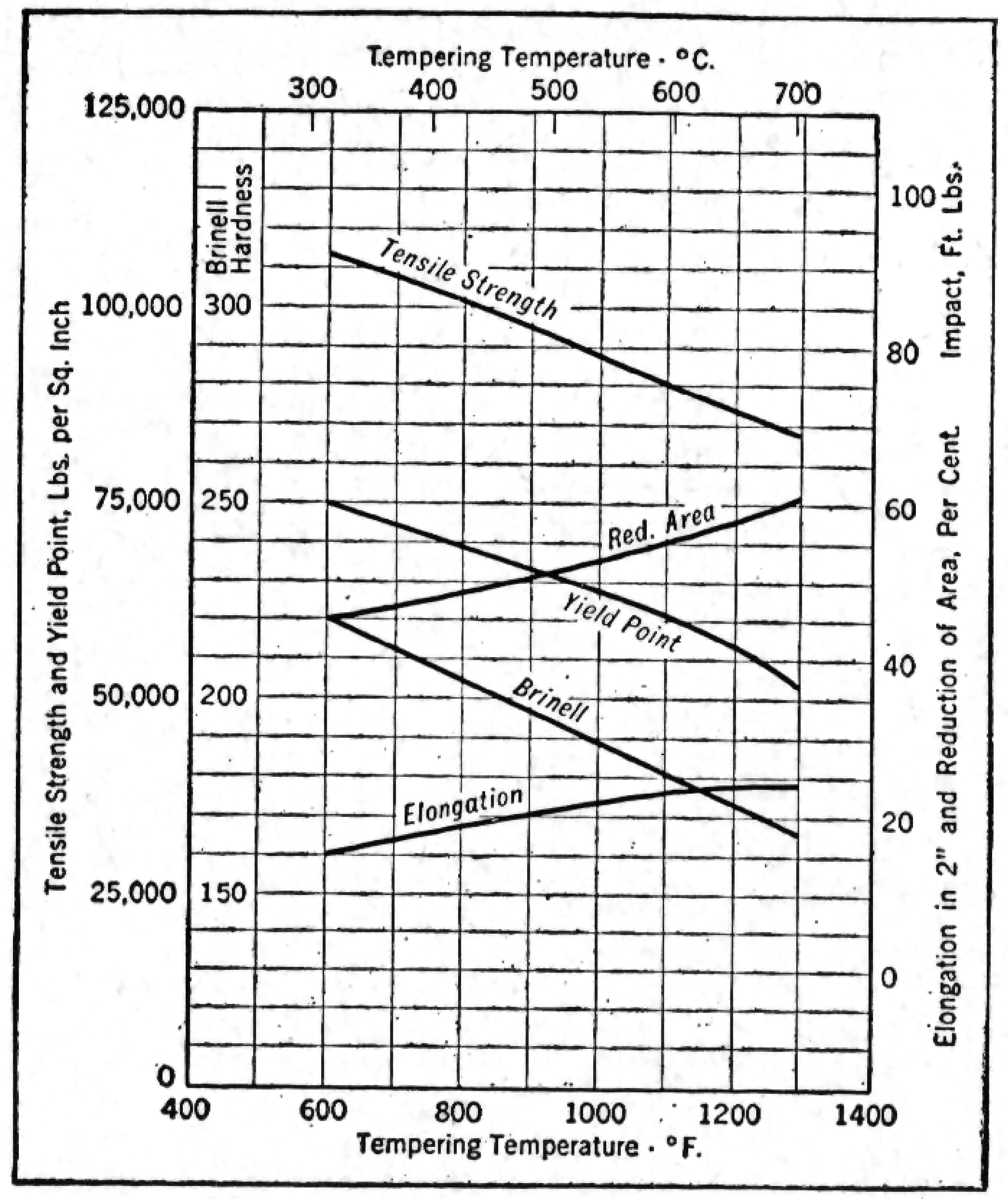
The impact-toughness curve in Fig. 10–20B illustrates the "blue brittleness" range which occurs between the approximate limits of 450F and 650F. This phenomenon is commonly ascribed to the precipitation of various oxides, nitrides, and possibly carbides, in the temperature range involved. The influence of tempering time and temperature on

TABLE 10–4

SPECIFIC EFFECTS OF ALLOYS IN STEEL

Element	Solid Solubility		Influence Upon Ferrite	Influence Upon Austenite (Hardenability)	Influence Exerted Through Carbide		Principal Functions
	In Gamma Iron	In Alpha Iron			Carbide Forming Tendency	Action During Tempering	
Aluminum Al	1.1% (Increased by C)	30% ±	Hardens considerably by solid solution	Increases hardenability mildly, if dissolved in austenite	Less than Fe (Graphitizes)	......	1. Deoxidizes efficiently 2. Restricts grain growth (by forming dispersed oxides or nitrides) 3. Alloying element in nitriding steel
Chromium Cr	12.8% (20% with 0.5% C)	Unlimited	Hardens slightly; increases corrosion resistance	Increases hardenability moderately, similarly to manganese	Greater than Mn; Less than W	Mildly resists softening	1. Increases corrosion and oxidation resistance 2. Increases hardenability 3. Contributes some strength at high temperatures 4. Resists abrasion and wear (with high carbon)
Cobalt Co	Unlimited	80% ±	Hardens considerably by solid solution	Decreases hardenability as dissolved	Similar to Fe	Sustains hardness by solid solution	1. Contributes to red hardness by hardening ferrite
Manganese Mn	Unlimited	15 to 18%	Hardens markedly; reduces plasticity somewhat	Increases hardenability moderately, similarly to chromium	Greater than Fe; Less than Cr	Very little, in usual percentages	1. Counteracts embrittlement by inevitable sulphur 2. Increases hardenability inexpensively 3. Forms batter resistant steel (high Mn, high C)
Molybdenum Mo	3% ± (8% with 0.3% C)	32% (Less with lowered temperature)	Provides age-hardening system in high Mo-Fe alloys	Increases hardenability strongly (Mo > Cr)	Strong; Greater than Cr	Opposes softening, by secondary hardening	1. Raises coarsening temperature of austenite 2. Deepens hardening 3. Raises hot strength, creep resistance, red hardness 4. Enhances corrosion resistance in stainless 5. Forms abrasion-resisting particles
Nickel Ni	Unlimited	25% ± (Irrespective of carbon content)	Strengthens and toughens by solid solution	Increases hardenability mildly, but tends to retain austenite with higher carbon	Less than Fe (Graphitizes)	Very little in small percentages	1. Strengthens unquenched or annealed steels 2. Toughens pearlitic-ferritic steels (especially at low temperature) 3. Renders high chromium-iron alloys austenitic
Phosphorus P	0.5%	2.5% (Irrespective of carbon content)	Hardens strongly by solid solution	Increases hardenability, similarly to manganese	Nil	......	1. Strengthens low carbon steel 2. Increases resistance to corrosion 3. Improves machinability in free-cutting steels
Silicon Si	2% ± (9% with 0.35% C)	18.5% (Not much changed by carbon)	Hardens with loss in plasticity (Mn < Si < P)	Increases hardenability more than nickel (Ni < Si < Mn)	Negative (Graphitizes)	Sustains hardness by solid solution	1. Used as general purpose deoxidizer 2. Alloy for electrical and magnetic sheet 3. Improves oxidation resistance 4. Increases hardenability of steels carrying non-graphitizing elements 5. Strengthens low alloy steels
Titanium Ti	0.75% (1% ± with 0.20% C)	6% ± (Less with lowered temperature)	Provides age-hardening system in high Ti-Fe alloys	Probably increases hardenability very strongly, *as dissolved*. Its carbide effects reduce hardenability	Greatest known (2% Ti renders 0.50% carbon steel unhardenable)	Persistent carbides probably unaffected. Some secondary hardening	1. Fixes carbon in inert particles (a) Reduces martensitic hardness and hardenability in medium chromium steels (b) Prevents formation of austenite in high chromium steels (c) Prevents localized depletion of chromium in stainless steels during long heating
Tungsten W	6% (11% with 0.25% C)	32% (Less with lowered temperature)	Provides age-hardening system in high W-Fe alloys	Increases hardenability strongly in small amounts	Strong	Opposes softening by secondary hardening	1. Forms hard, abrasion resistant particles in toolsteels 2. Promotes red hardness and hot strength
Vanadium V	1.5% ± (4% with 0.20% C)	Unlimited	Hardens moderately by solid solution	Increases hardenability very strongly, *as dissolved*	Very strong (V < Ti or Cb)	Maximum for secondary hardening	1. Elevates coarsening temperature of austenite (promotes fine grain) 2. Increases hardenability (when dissolved) 3. Resists tempering and causes marked secondary hardening

Adapted from The Functions of the Alloying Elements in Steel *by Edgar C. Bain, as published by ASM.*



Composition, Per Cent

Carbon..............0.30-0.40
Manganese...........0.60-0.90
Phosphorus........0.045 Max.
Sulphur...........0.055 Max.

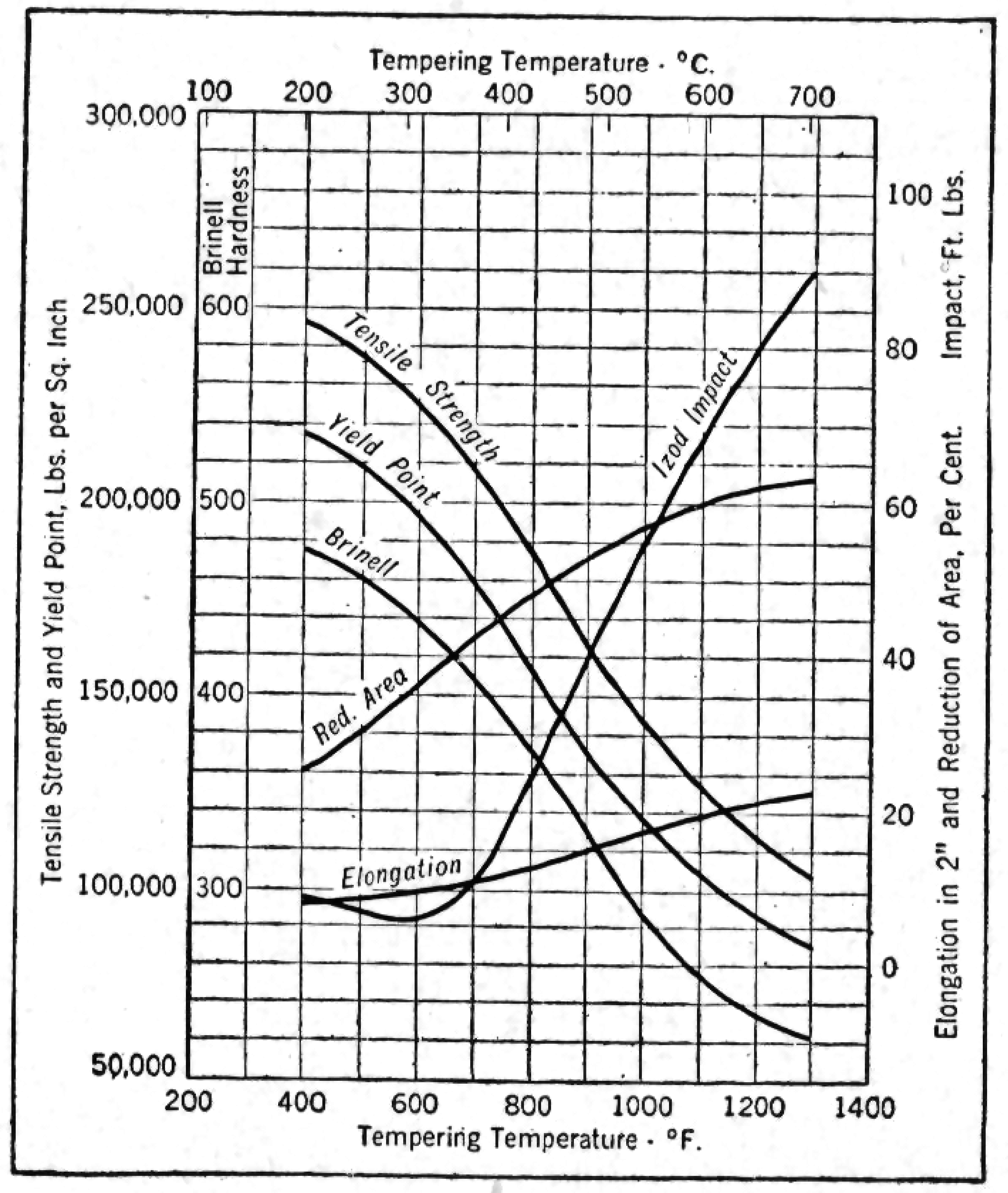
Approximate Critical Range

Ac_1 1365F
Ac_2 1415F
Ac_3 1485F

Heat Treatment

Quenched from 1525-1575F
Quenched into oil
Tempered as indicated

FIG. 10-20A. Influence of tempering on mechanical properties of a medium carbon steel, SAE 1035, which has been oil quenched and is in small sizes of ½ in. to 1½ in. diam or thickness. (Courtesy of International Nickel Company.)



Composition, Per Cent

Carbon..............0.35-0.45
Manganese...........0.60-0.90
Phosphorus.........0.04 Max.
Sulphur............0.05 Max.
Nickel..............1.00-1.50
Chromium...........0.45-0.75

Approximate Critical Range

Ac_1 1355F
Ac_2 1380F
Ac_3 1395F

Heat Treatment

Quenched from 1475-1525F
Quenched into oil
Tempered as indicated

FIG. 10-20B. Influence of tempering on mechanical properties of a nickel-chromium steel, SAE 3140, which has been oil quenched and is in small sizes of ½ in. to 1½ in. in diam or thickness. (Courtesy of International Nickel Company.)

TABLE 10-5

HARDNESS OF PLAIN CARBON TOOL STEEL AS AFFECTED BY TEMPERATURE AND TIME OF TEMPERING

TEMPERING TEMP. (F)	HARDNESS AS-QUENCH (ROCK. C)	ROCKWELL C HARDNESS AFTER HOURS OF TEMPERING							
		1 Hr	2 Hr	4 Hr	8 Hr	16 Hr	32 Hr	6 Hr	128 Hr
200	68	68	68	68	67	67	67	67	66
300	68	66	66	65	65	64	64	62	62
400	68	62	61	61	61	60	60	60	59
500	68	61	60	58	57	57	56	55	55
600	68	55	55	53	52	51	51	51	50
700	68	52	51	50	49	49	49	47	46
800	68	47	46	45	45	44	44	43	42

the hardness of a 1.10 per cent carbon steel is shown in Table 10-5 and Fig. 10-21.

By selecting the proper tempering temperature, it is possible to obtain any combination of physical properties within the capacity of the steel, from the maximum hardness, to an intermediate hardness combined with considerable toughness, to a minimum hardness combined with maximum toughness.

Changes brought about in the mechanical properties of steel by tempering are attributed primarily to the precipitation and coalescence of

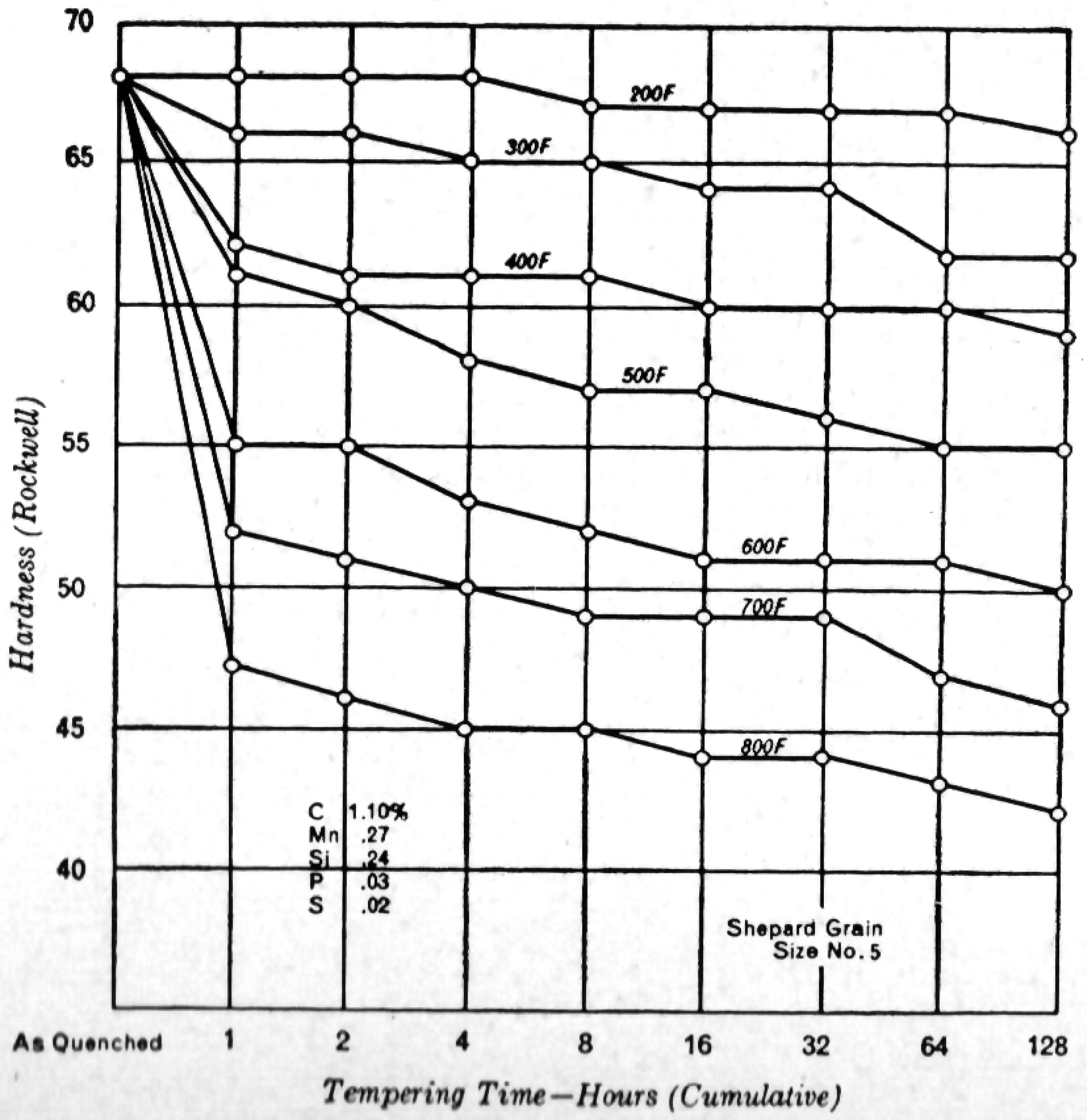


FIG. 10-21. Hardness of plain carbon tool steel as affected by temperature and time of tempering.

the carbon, or carbide particles, present in a highly dispersed state in the martensite. With increasing tempering temperature and time, these particles, present on certain planes of the crystals, migrate or diffuse when the metal is heated and combine to form large aggregates. By thus reducing the *number* of carbide particles within the grains, certain crystallographic planes of normally easy slippage are deprived of the slip interference of these carbides and, consequently, resistance to slip is reduced along those planes. Since hardness is defined as resistance to deformation, factors which lower the resistance to deformation (or slip) also contribute to a lower hardness. It should be emphasized that tempering produces no change in the *size* of the grains.

Because of high internal stresses induced partly by the increase in volume when the austenite transforms to martensite, tempering should be undertaken immediately following the quenching, or even before the steel becomes entirely cold, especially if the part is of a complicated shape. Quenching cracks frequently appear when hardened steel is retained at normal temperatures without relieving the stresses. Case-carburized parts are stress-relieved at temperatures of 300 to 350F to avoid possible hairline cracks which often appear during grinding operations.

As hardened steel is heated to progressively higher temperatures, the primary microstructure gradually breaks down above 300F and forms secondary constituents. Thus, martensite, when reheated from 350F to 750F, changes to troostite. When heated from 750F to 1250F, a structure known as sorbite forms. These structures represent lower hardness and higher ductility than martensite. The troostite derived by tempering differs from that obtained by the direct transformation of the austenite, in that the carbides tend to be more spherical than lamellar, and the acicular appearance of the martensite will remain even after a prolonged heating. Compare Figs. 10–8 and 10–9.

Tempering is carried out commercially by heating to the desired temperatures in oil, lead, salts, or in air circulating furnaces that are heated electrically or with liquid or gaseous fuels. The time of holding at a specific temperature is governed by the size of the part and the properties desired. Quenching after tempering is generally optional, as no effect on the results comes from cooling from below the Ac_1 temperature. Certain high chromium-nickel steels are preferably quenched in oil from the tempering temperature, to avoid brittleness. Individual parts such as chisels, punches, screw drivers, and lathe tools, when made of plain carbon steel, are sometimes tempered by observing the color of a film of oxide, which forms on their polished surface as the steel is heated to temperatures from about 400 to 600F. The principal colors and the approximate corresponding temperatures for plain carbon steel are given in Table 10–6.

The color basis of tempering places a premium upon experience, proper lighting, and ability to differentiate between colors. Furthermore, its reliability is in inverse ratio to the size of the piece, and it applies principally to carbon steels.

TABLE 10–6

SEQUENCE OF PRINCIPAL TEMPER COLORS AND CORRESPONDING TEMPERATURES FOR CARBON STEEL

Temperature (F)	*Temper Color*
420	Very faint yellow
450	Pale straw
470	Deep straw
500	Yellow-brown
550	Dark blue
600	Light blue

10–14. Austenite Transformation at a Constant Subcritical Temperature. Instead of cooling steel rapidly from the austenitic range to obtain martensite and then reheating to toughen it in the customary manner, there has been developed within recent years a modified form of hardening and tempering called *austempering*. The process consists of quenching the steel in a molten salt or metal bath maintained at some constant temperature, usually between 800 and 500F, and holding it in the bath for a sufficient time to cause an isothermal transformation of the austenite into intermediate products having the structural characteristics of the temperature of transformation. On any temperature level, the time may be varied to provide for either a partial or a complete transformation of the austenite. When only a partial change has taken place at the higher temperature, the part may be removed and cooled more quickly in air or by a liquid quench to transform the remainder of the austenite to martensite. Usually sufficient time is taken to insure a complete transformation. When the transformation takes place at about 500F, the structure consists of a ferrite carbide mixture called *bainite*. It is characterized by a substantially greater toughness for equivalent tensile strength than is obtained by quenching and tempering separately. A vast improvement is evidenced by the higher impact strength and a greater reduction of area, as shown in Table 10–7.

For the formation of 100 per cent bainite, cooling must be uniform throughout the section of the part. Since this cannot be achieved except with small sections, the austempering process is applicable only to parts within a given critical size. For plain carbon steels of equal diameter, its effectiveness varies as the amount of manganese. Alloy steel parts containing elements which tend to stabilize the austenite (lower critical cooling rate) may be austempered up to about 1 in. in diameter. The best combination of properties is obtained with steels containing from

0.60 to 1.20 per cent of carbon and when the hardness varies from 45 to 55 Rockwell C.

When data are plotted graphically to indicate the time required at each temperature level for specimens of similar size and composition to transform at constant temperature, we obtain the isothermal or "S" curves. Fig. 10–22 shows a typical S curve as well as the structures and hardnesses obtained after a 0.89 per cent carbon steel was held at the temperatures plotted on the vertical axis for the required reaction time plotted logarithmically on the horizontal axis. Although the fundamental characteristics of these curves are similar for all steels, nevertheless, each grade of steel will have a different S curve because of the influence of the composition on the rate of the austenite transformation.

TABLE 10–7

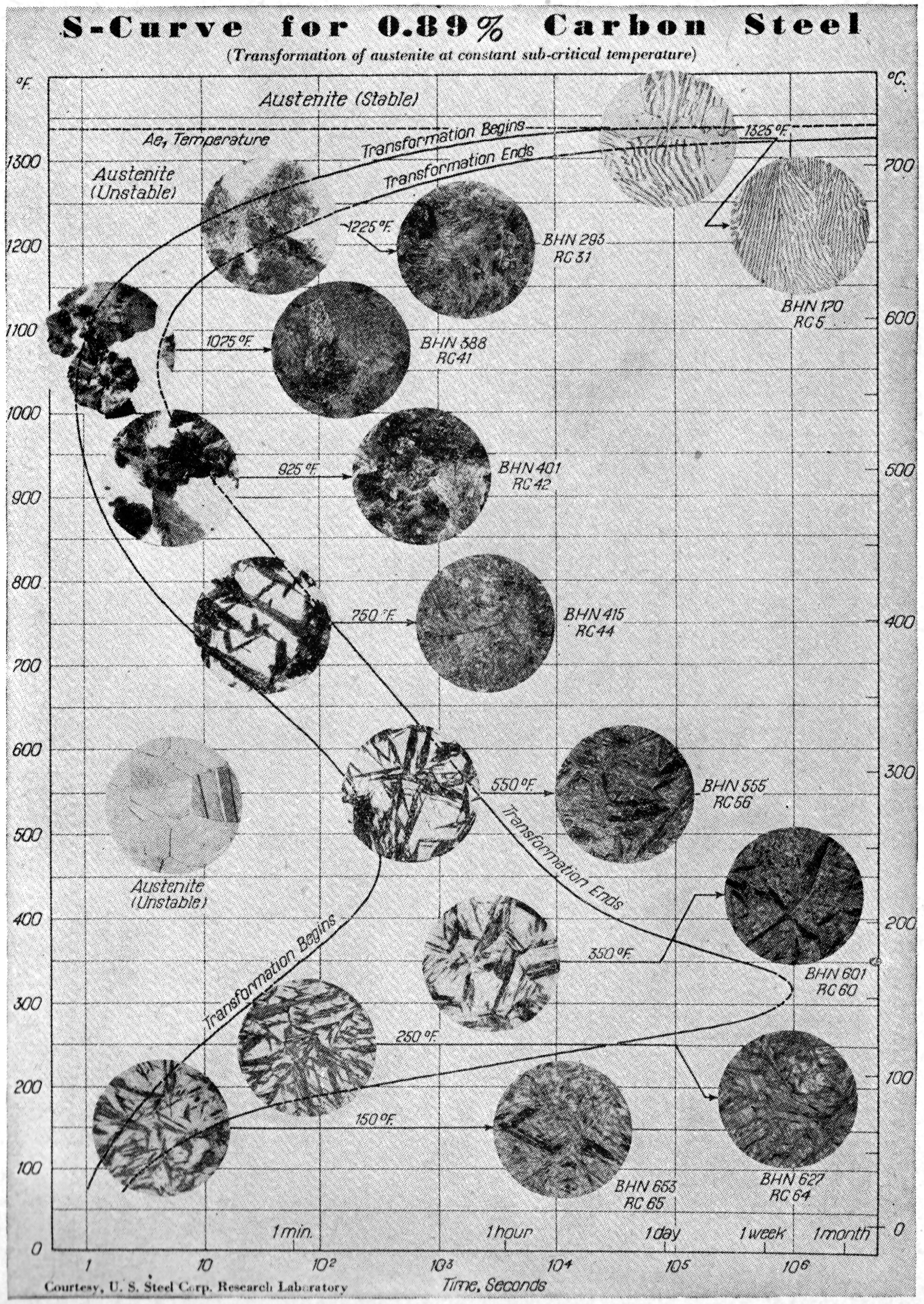
Relative Mechanical Properties of 0.74 Per Cent Carbon Steel after Austempering and Quenching and Tempering*

Mechanical Properties	Austempered	Quenched and Tempered
Rockwell C hardness	50.4	50.2
Yield point, psi	151,300	121,700
Tensile strength, psi	282,700	246,700
Elongation, per cent in 6 in.	1.9	0.3
Reduction of area, per cent	34.5	0.7
Impact, ft-lb (0.180 in. round, unnotched specimen)	35.3	2.9

*Davenport, Roff, and Bain, *Transactions ASM*, Vol. 22 (1932), p. 385.

10–15. Hardenability. It has been pointed out that the hardness of a particular quenched steel varies with its cooling velocity. And, since cooling rates are highest at the surface of a part, the hardness decreases toward the core in direct relation to the size of the section. The depth to which a steel of a given mass reaches its maximum hardness at any cooling rate is primarily a function of its composition. It is also influenced, as described above, by the austenitic grain size. Since the tensile and yield strengths vary directly as the hardness, it is desirable to be able to predict the approximate hardenability of various steels. This information is useful either when designing strength members or when a high surface hardness and a strong tough core are required in a machine part. Several methods which may be used for this purpose are (1) hardness explorations from surface to core, as shown in Fig. 10–19; (2) the transformation time at any temperature level, as determined by the S curve; (3) the microstructure; and (4) the end-quench or Jominy test.

The end-quench test consists of cooling a bar, 1 in. in diameter and 4 in. long, from its critical range to normal temperature in a stream of



Courtesy, U. S. Steel Corp. Research Laboratory

Fig. 10–22. Typical S curve.

water directed against its bottom face as it is suspended vertically in a fixture. Since all variations of the cooling rate are obtained, from the most rapid at the lower end to that corresponding to an air cooling at the upper end, hardness differences will likewise prevail along the entire length of the bar. After the sample has become cold, two flat surfaces are ground to a depth of 0.15 in., 180 degrees apart. Hardness readings with the Vickers or Rockwell machines (C scale) are then taken along the flat surfaces at $^1/_{16}$-in. intervals. These hardness values, when correlated, in a range of diameters, with the known cooling rates at the center of steels of similar analyses, will enable one to foretell their hardenability or the depth to which they will appreciably respond when quenched in either water or oil.

This method also has application as a means of determining weldability, because hardenability and weldability vary inversely. Since steels of high hardenability will become hardened by the cooling rates prevailing in certain forms of welding, they will lack the ductility so desirable in weldments.

10–16. Grain Size. Because grain size influences the mechanical properties and hardenability, attempts have been made to control the initial grain size and to measure it according to some standards. The methods of control include the use of nuclei-forming elements during the solidification of the steels. Aluminum is chiefly used for this purpose, while alloying elements such as vanadium, molybdenum, and tungsten largely inhibit grain coarsening tendencies during subsequent operations.

One method, among several, which may be used to determine the grain size is known as the McQuaid-Ehn method. This consists of heating a low-carbon or low-alloy steel to 1700F for 8 hr, in contact with a carburizing mixture, then following by a slow cool. This treatment causes a sufficient absorption of carbon by the steel at its surface to produce a hypereutectoid zone. When cold, a transverse section is polished, etched, and examined under the microscope at a magnification of 100 diam. The proeutectoid pearlitic grains in the high-carbon zone, being well outlined by a carbide network, are then measured and classified according to ASTM standard grain sizes, which are numbered from 1 to 8 as shown in Fig. 10–23. Grain sizes from 1 to 4 inclusive are listed as coarse, while those from 5 to 8 are considered as fine. Other methods by which grain size might be compared are (1) by heating medium-carbon steels to the austenitic range, normalizing or cooling at a uniformly moderate rate, and etching and examining microscopically for comparison; (2) by heating bars of like analysis and size to four different temperatures, increasing at intervals of 50 degrees from 1450 to 1600, quenching in water, and fracturing for visual examination.

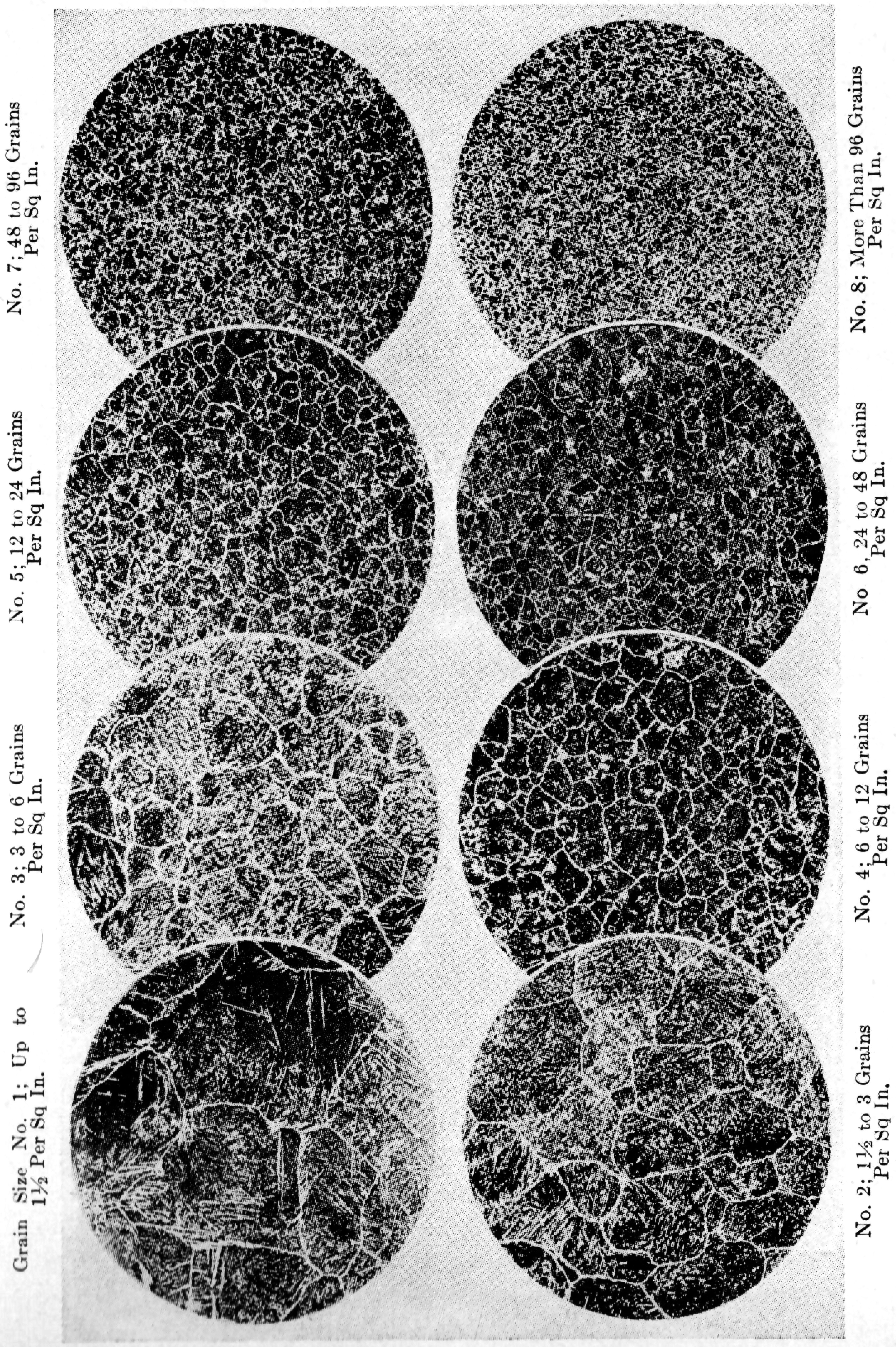

Grain Size No. 1; Up to 1½ Per Sq In.
No. 3; 3 to 6 Grains Per Sq In.
No. 5; 12 to 24 Grains Per Sq In.
No. 7; 48 to 96 Grains Per Sq In.
No. 2; 1½ to 3 Grains Per Sq In.
No. 4; 6 to 12 Grains Per Sq In.
No. 6; 24 to 48 Grains Per Sq In.
No. 8; More Than 96 Grains Per Sq In.

FIG. 10–23. Standard grain sizes for steels. Carburized and slowly cooled to develop cementite network. Magnified 100 diam. (Micros Courtesy of Timken Roller Bearing Co.)

10–17. Casehardening. In the heat-treating process known as casehardening, a hard wear-resisting outer layer or shell is produced over a softer and more ductile core or interior of an iron-base alloy by changing its surface composition.

10–18. Processes. Casehardening may be effected by means of solid materials, usually called compounds, or by means of liquids and gases. As will be pointed out later, the solids function through the medium of gases liberated by them at elevated temperatures; and, therefore, the chemistry of the process is fundamentally similar to where gases of comparable analyses are introduced directly into the furnace or retort.

10–19. Carburizing. Case- or surface-hardening by means of solid materials is known as *pack carburizing* and is the method most widely used industrially. The carburizing materials comprise hardwood charcoal, charred leather, or charred bone and coke, with some energizers. One typical commercial mixture conforms to the following specifications:

Hardwood charcoal	53–55 per cent
Solvay coke	30–32 per cent
Barium carbonate	10–12 per cent
Calcium carbonate	3–4 per cent
Sodium carbonate	2–3 per cent

These are bonded with heavy oil, tar, or molasses and formed into pellets about ¼ in. in diameter. The coke does not actively react as a carburizer but reduces shrinkage and acts as a filler. The carbonates, of which barium ($BaCO_3$) is the most commonly used, function principally by furnishing CO at the carburizing temperature to sustain carburization for long periods. Provided the *fines* (pulverized material) are sifted and discarded, commercial compounds may be re-used, although it is customary to add from 10 to 20 per cent of new material to the old. The use of animal charcoals is now largely supplanted by the wood charcoal base compounds, although under certain circumstances the animal charcoals may also well be used.

10–20. Steels for Carburizing. It is recalled that the quenched hardness of steel is a function of the amount of carbon it contains and that steels of less than 0.25 per cent carbon do not respond appreciably in increased hardness to the usual hardening process but retain their initial characteristics of toughness and ductility. When heated to the austenitic temperature range and held a sufficient time in sealed containers in contact with carbonaceous materials, such steels will absorb carbon and may, upon subsequent heat treatment, be produced with hard surfaces of variable depth surmounting their initial tough ductile core.

If a machine part possesses the dual properties of a high surface hardness to resist frictional wear without the brittleness usually associated with hardness, it is possible to utilize such a part for service where it is required to withstand impact stresses—for example, gears and cams. In order, therefore, to obtain these advantages, steels selected for carburizing must be of the low-carbon type in both the plain carbon and alloy groups, with the carbon ranging from 0.10 to 0.20 per cent. Greater strength of core and better machining qualities favor the use of the higher carbon. With correct subsequent heat-treating practice, steels with carbon up to 0.45 per cent may be used. However, it is generally acknowledged that the rate of diffusion of the carbon within the steel for a given temperature and time varies inversely as the initial carbon content. Furthermore, steels selected for carburizing should be free of all defects such as piping, lamination, and segregation, since all such defects are accentuated by long exposures to the temperatures employed in the process. The presence of oxides increases the difficulties of carburizing appreciably. Alloying elements also influence the rate of penetration of the carbon, as well as its diffusion.

Apart from the plain carbon steels SAE 1010, 1015, and 1020 and the corresponding NE (National Emergency) steels, the alloy steels most frequently carburized are SAE 2315 (Ni, 3.25–3.75 per cent), 3115 (Ni, 1–1.50 per cent Cr, 0.45–0.75 per cent), 2512 (Ni, 4.75–5.25 per cent), 4615 (Ni, 1.65–2 per cent; MO 0.20–0.30 per cent), and 6115 (Cr 0.80–1.10 per cent; V 0.18 per cent).

10–21. Packing. After the parts have received their preliminary machining and cleaning, they are packed with the compound in suitable steel containers. When full, the boxes are fitted with a cover which is luted with fireclay to prevent the escape of the gases produced in the box. The boxes are then heated in appropriate furnaces to a temperature of from 1650–1750F and held for a sufficient time to produce a required depth of carburization. The usual time of holding varies from 6 to 20 hr, depending on several factors such as type of steel, depth of case desired, type of carburizer used, temperature and size or mass of parts. The average time, however, is between 8 and 10 hr. The boxes are made of gray cast-iron, pressed steel, or more commonly a nickel-chromium heat-resistant cast-steel.

10–22. Chemistry. Since practically no carbon is soluble in ferrite, carburizing temperatures vary from 100 to 200F above the Ac_3 or the line *GS* in Fig. 9–6. Lower temperatures (but above Ac_3) require longer carburizing time, while higher temperatures tend to produce coarse-grain structure. As the steel is austenitic at these temperatures, its surface absorbs carbon furnished through the medium of carbon monoxide that is generated by action of the carbon and the oxygen present in the container, $2C + O_2 \rightarrow 2CO$. The mechanism of carburization may then be shown by equation: $2CO + 3Fe \rightarrow Fe_3C + CO_2$. Thus iron carbide, produced in the outer layers of the metal, slowly diffuses from the surface inward, while the CO_2 reacts with carbon, $CO_2 + C \rightarrow 2CO$. Since the rate of carbon absorption into the surface layers is higher than its rate of diffusion within the metal, carbon in the surface may be increased to an amount equal to that present in tool steel. Such a steel, therefore, when quenched in oil or water from the proper temperature, will respond in hardness in a manner similar to tool steel.

The depth of the case or the zones within which the composition has been materially altered usually varies from 0.040 to 0.080 in., and the carbon content of the outer layers is 1.20 per cent or over.

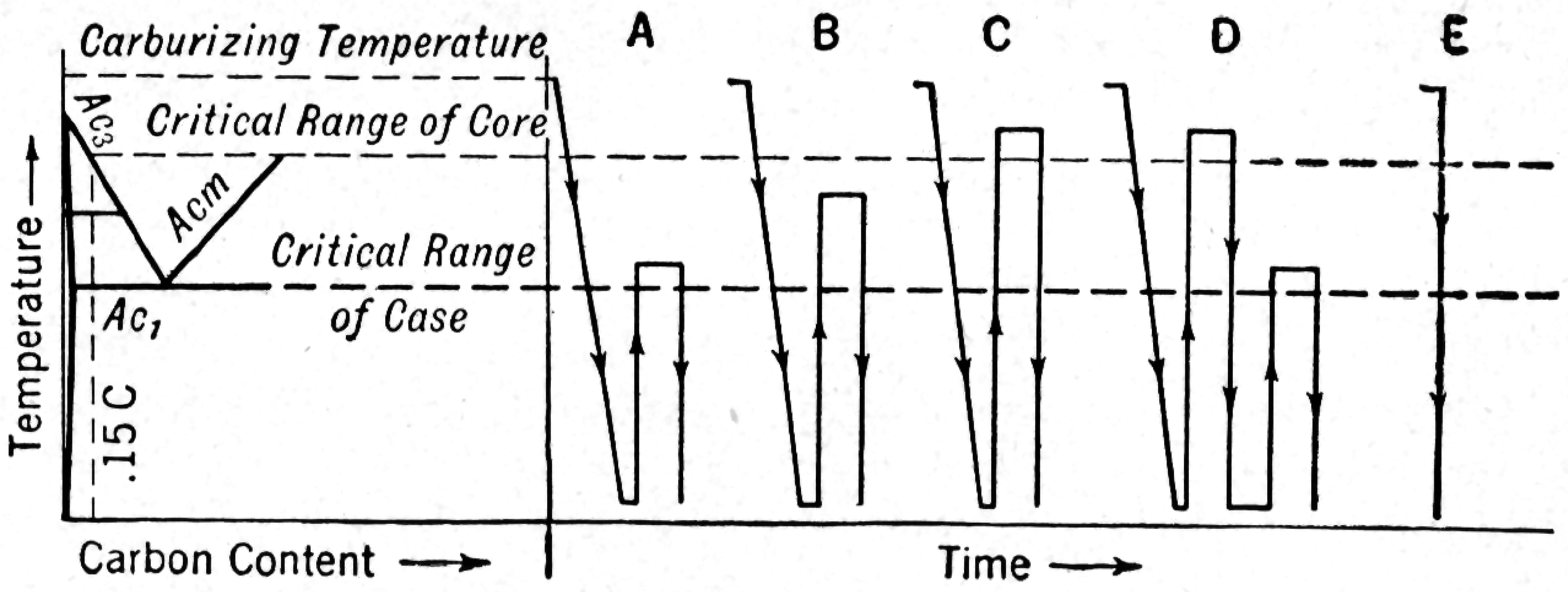
10–23. Heat Treatment after Carburizing. After the carburizing cycle, several heat treatments may be used for the development of the hard surface. The governing factors in the selection are largely the type of steel, whether fine- or coarse-grain, and the mechanical properties desired in the finished product to meet required service conditions. These treatments may vary from a direct quench from the carburizing temperature, which is common practice with fine-grain steels, to a double quench for coarse-grained steels from above the Ac_3 and Ac_1 to refine the grain structure of the core and the case, respectively. As shown by Fig. 10–24, other methods are also practiced for various purposes.

10–24. Gas Carburizing. Carburizing, effected in a manner fundamentally similar to pack carburizing, takes place when steels of comparable analyses are subjected to the action of carbonaceous gases introduced directly into continuous operating or batch type furnaces or into rotating retorts. However, the source of carbon is some hydrocarbon gas such as both raw and diluted natural gas, propane, butane, or manufactured gas. Subsequent heat treatment is similar to that followed in pack carburizing. The influence of time and temperature on penetration is shown in Fig. 10–25.

The chemistry of carburizing involves the dissociation of these gases to form methane (CH_4), hydrogen (H_2), and carbon: $CH_4 \rightarrow 2H_2 + C$. The carbon is absorbed by the metal when heated to the austenitic temperature of 1600 to 1750F.

Gas carburizing produces a case of commercial depths in less time than pack carburizing because of the saving in time required to heat the carburizer and the containers. The process also lends itself better to continuous production practices. The use of gas carburizing is increasing rapidly where suitable gases are readily available.

10–25. Liquid Bath Carburizing. A shallow but hard case may also be produced on low-carbon steels by immersing the parts in a bath of



Treatment	Case	Core
A (Best adapted to fine-grained steels)	Refined; excess carbide not dissolved	Unrefined; soft and machinable
B (Best adapted to fine-grained steels)	Slightly coarsened; some solution of excess carbide	Partially refined; stronger and tougher than A
C (Best adapted to fine-grained steels)	Somewhat coarsened; solution of excess carbide favored; austenite retention promoted in highly alloyed steels	Refined; maximum core strength and hardness; better combination of strength and ductility than B
D (Best treatment for coarse-grained steels)	Refined; solution of excess carbide favored; austenite retention minimized	Refined; soft and machinable; maximum toughness and resistance to impact
E (Adapted to fine-grained steels only)	Unrefined with excess carbide dissolved; austenite retained; distortion minimized	Unrefined but hardened

FIG. 10–24. Diagrammatic representation of different treatments subsequent to carburization, and the case and core characteristics obtained. (Courtesy of International Nickel Company.)

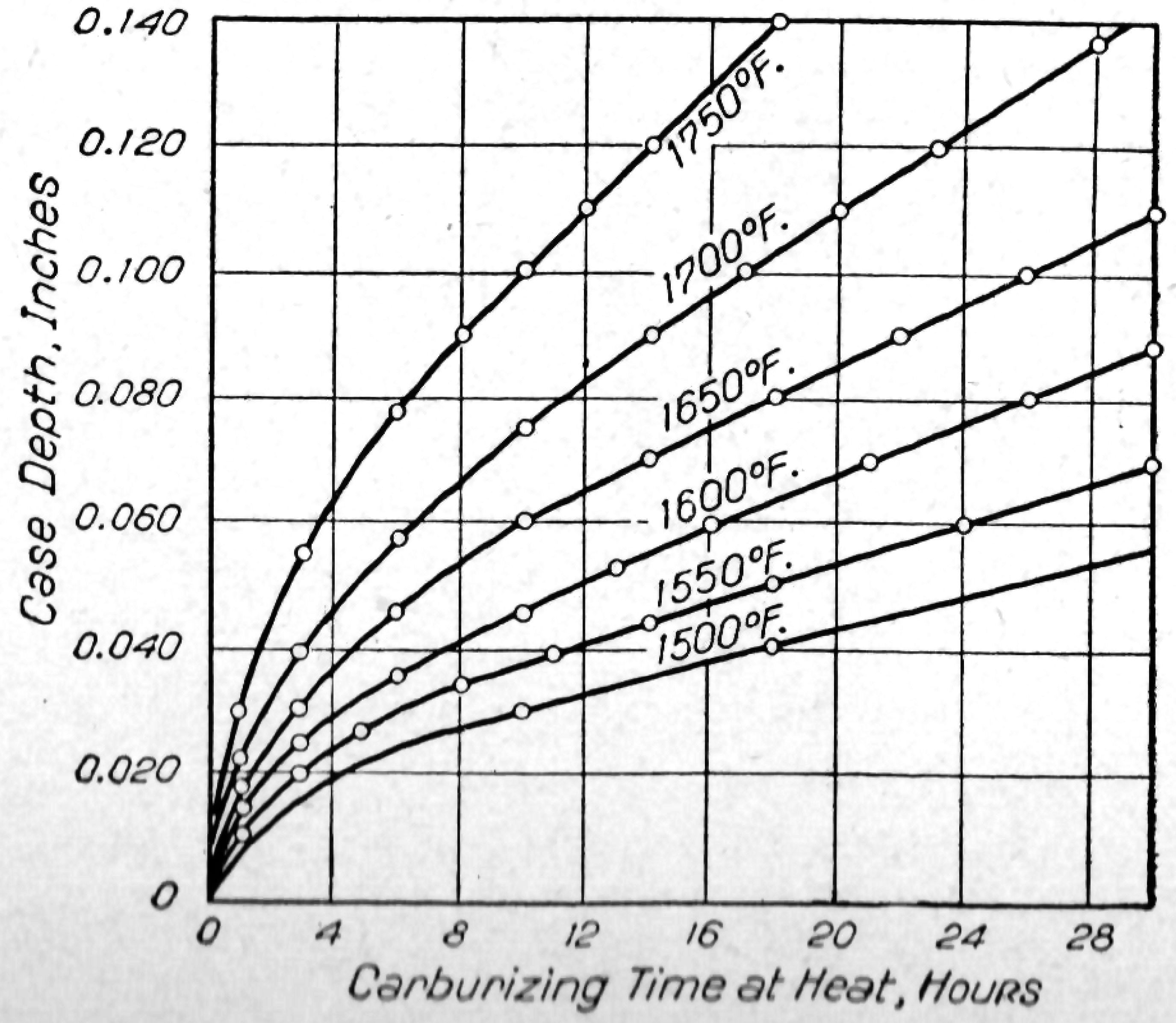


FIG. 10–25. Time-temperature penetration curves with natural gas as carburizer (Schlumpf).

molten cyanide salts for a comparatively short time and quenching in water, brine, or oil directly from the carburizing temperature. The salts may be sodium cyanide ($NaCN$) or potassium cyanide (KCN). However, because of lower cost and greater efficiency, sodium cyanide is now almost universally used.

The composition of a cyanide bath consists of 30 to 45 per cent sodium cyanide, the balance being sodium carbonate and sodium chloride, which act as fixatives and prevent too rapid volatilization of the base cyanides. The bath is operated at a temperature of 1450 to 1600F with the time of immersion ranging from 15 min to 1 hr, depending on the depth of case desired and the size of the parts. An average time of 15 or 20 min produces a case of approximately 0.004 in. thick in a highly concentrated bath.

Because of the deterioration caused by the continued use of cyanide at the high temperatures employed, it is necessary to replenish frequently with fresh cyanide of 75 or 98 per cent concentration.

Liquid carburizing with cyanides is effected by the absorption by the metal of both carbon and nascent nitrogen, liberated when the cyanide decomposes upon exposure to heat and oxygen, as shown by equations:

$$2\,NaCN + O_2 \rightarrow 2\,NaCNO$$
$$4\,NaCNO + \text{heat} \rightarrow 2\,NaCN + Na_2CO_3 + CO + 2N$$

Cyanide carburizing is best adapted to the production of a superficial hard case on small parts such as nuts, screws, bolts, small gears, pawls, and similar parts which are usually handled in large batches in wire containers and suspended in the bath.

Because parts are protected from oxidation during the heating in a liquid bath and because some of the salts adhere to the surface, parts heated in cyanide and other salt baths retain their bright machined surfaces after being heat-treated.

For these reasons as well as to avoid decarburization, dies, taps, etc., are often heated for hardening in liquid baths.

The depth of case in cyaniding is not proportionate to the time of exposure, except for the first few minutes; therefore, the process is not adapted to the formation of a heavy case. Cyanide containers should be provided with hoods and adequate ventilation to remove the obnoxious fumes emitted; and, because cyanides are violent poisons, extreme care is required in handling.

10-26. Activated Liquid Baths. Activating agents such as polymerized hydrocyanic acids, calcium cyanide, calcium cyanamide, barium chloride, and calcium and sodium chlorides are added to cyanide baths to promote carburizing by means of carbon without the nitrogen. It is stated that the structure of the case is improved and that better properties are obtained than with cyanides alone.

The influence of these activating agents on the depth of the case under uniform conditions of time and temperature is shown in Fig. 10-26.

Another method for obtaining a superficial case consists of bubbling dissociated ammonia through the cyanide salt bath to increase the nitrogen absorption by the steel. This is known as *Chapmanizing*.

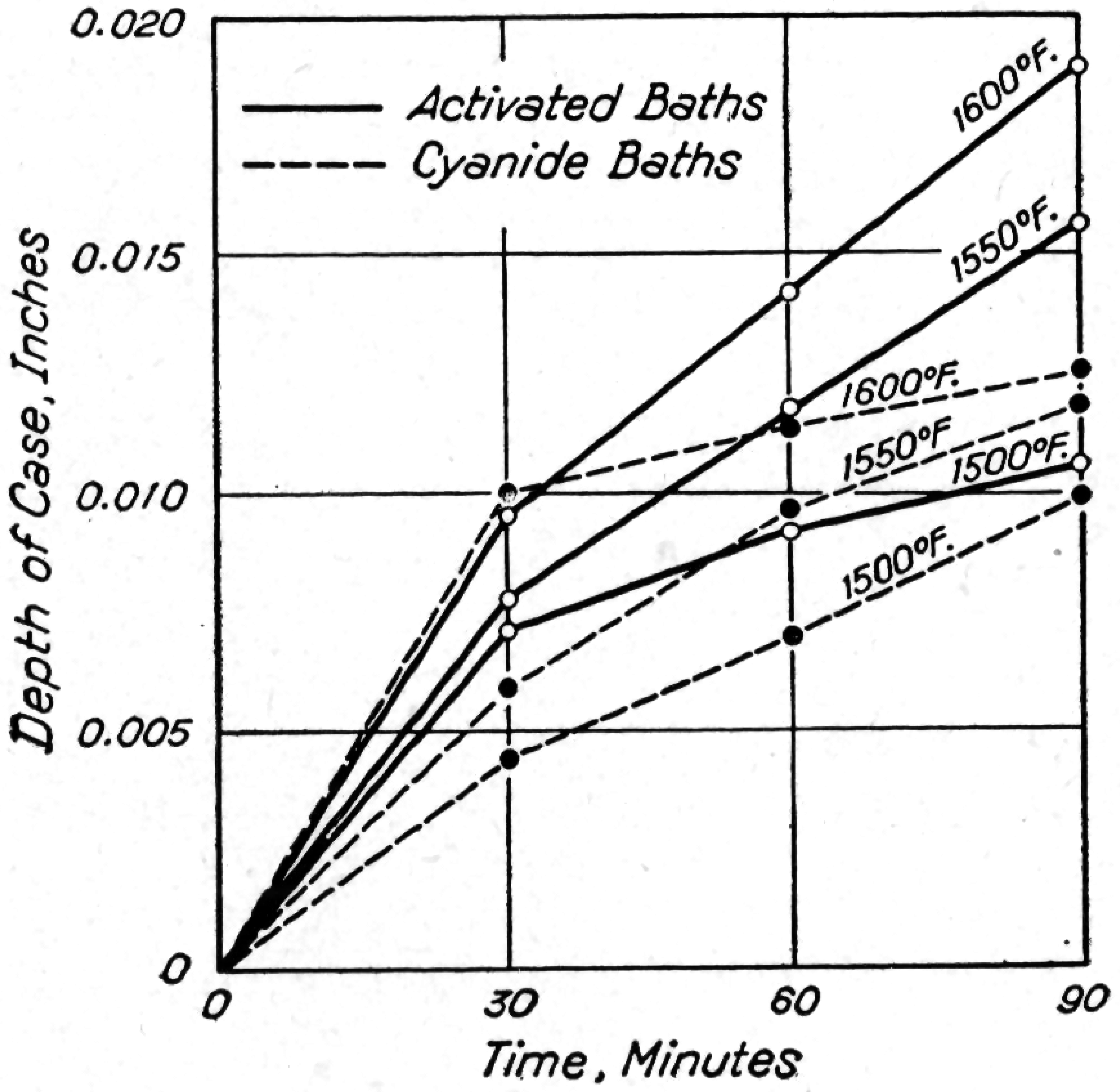


FIG. 10-26. Case depths for activated baths and cyanide casehardening bath. (Adapted from Beckwith, *Transactions ASM*, Vol. 26, No. 3, 1938.)

10-27. Nitriding. Nitriding is a process of effecting a case- or surface-hardness by heating steels of suitable analyses to a temperature of from 950 to 1000F in sealed containers, into which there is continually passed a nitrogenous gas usually obtained by the dissociation of ammonia according to equation: $2NH_3 \rightarrow 2N + 3H_2$. The nascent nitrogen combines with certain elements such as aluminum, chromium, molybdenum, and manganese, which are present in all nitriding steels, forming nitrides; these nitrides not only produce higher hardnesses than are obtainable by carburizing but are also more stable at elevated temperatures than the carbides resulting from carburizing.

While similar to carburizing in that both processes are means of producing hard surfaces, nitriding differs widely from carburizing in that (1) only alloy steels may be used, (2) the steels are preferably heat-treated before nitriding to obtain a sorbitic structure, (3) nitriding temperatures are much lower, (4) no heat treatment is necessary after nitriding, (5) hardness up to 1250 Vickers-Brinell is obtainable, and (6) the surface has greater resistance to corrosion.

Some of the disadvantages of nitriding are (1) only a very thin case is produced, (2) only special alloy steels may be used, (3) time of heating varies from 50 to 100 hr—a 50-hr cycle gives a case depth of approximately 0.015 in., while a 100-hr cycle gives a case depth of approximately 0.025 in., (4) mainly because of (2) and (3) the process is more expensive than carburizing.

Some automotive parts adapted to casehardening processes are shown in Table 10–8. The 0.040 in. to 0.060 in. case depth shown for steering knuckle pins, side pinion axles, reverse idler gear shafts, and counter gear shafts is actually more case depth than is necessary to satisfy service requirements put on parts such as these. However, this added case depth is to avoid the necessity of straightening to extremely accurate degree before grinding. Likewise, camshafts are carburized deeper than necessary to satisfy service requirements in order to compensate both for inaccuracies of machining due to length of these parts and for distortion due to heat treatment and also to insure sufficient case after grinding for necessary hardness and wear resistance.

10–28. Flame Hardening. Flame hardening consists of heating localized areas on large or irregular shapes of hardenable steels, gray cast-iron, pearlitic malleable iron and steel castings with the oxyacetylene flame and cooling in air or by a water spray quench. The process is particularly adapted for surface-hardening large gear teeth, cylindrical shafts, and small contact spots for wear resistance. Use is made of a specially constructed multiflame, water-cooled heating and quenching tip, which may be operated either manually or mechanically. The speed of travel of the heating head and the number of heating holes determine the depth to which the surface hardens on quenching; and, with the average speed of 6 to 8 in. per min, a 1/8 to 3/16 in. penetration may be obtained.

Commercial constructional steels suitable for flame hardening are SAE 1040 to 1070. Susceptibility to surface cracks is encountered with steels of higher carbon than 0.70 per cent, unless less drastic cooling than a water quench is used. Alloy steels containing elements contributing to a low critical cooling rate may be hardened satisfactorily with 0.35 per cent carbon.

Cast-steels are preferably flame hardened in the normalized and drawn condition; otherwise, the incidental stresses may cause cracking. Gray cast-iron possessing a moderate amount (0.50 per cent) of combined carbon (pearlite) may be hardened satisfactorily, and surfaces of gray iron lathe ways are flame hardened for wear resistance. Pearlite malleable iron may also be flame hardened in a similar manner to steel and gray iron of comparable pearlitic composition.

The flame hardnesses of various steels and cast-irons are given in Tables 10–9 and 10–10.

TABLE 10–8

TYPICAL AUTOMOTIVE CARBURIZING APPLICATIONS AND REQUIREMENTS

Case Depth	Typical Parts Made from Low-Carbon Steel	Surface Condition When Treated	Requirements	Typical Parts Made from Medium-Carbon Steel	Requirements
Up to 0.020″	Push rod balls. Push rod sockets. Speedometer gears. Shackle bolts. Shifter forks. Tie rod ball studs. Tie rod ball stud sockets.	Finished before treatment except for possible polishing operation.	High degree of wear resistance. Clean surface after treatment.	Transmission gears. Transmission main shafts and synchronizer sleeves. (Surface generally finished before treatment.)	Maintain or increase surface carbon for higher degree of wear resistance and greater fatigue resistance. Resistance to high occasional or shock loading. Clean surface after treatment.
	Water pump shafts.	When nitrided 0.0003″ to 0.001″ per side removed for maximum wear resistance.			
0.020″ to 0.40″	Pitman arm ball studs. Intermediate steering arm ball studs.	Finished before treatment except for possible polishing operation.	High degree of wear resistance. Sufficient strength to withstand service loads. Clean surface after treatment.	Transmission gears. Ring gears. Drive pinions. (Surface-finished before treatment except for lapping operation.)	Increase carbon content at surface for greater wear resistance, load carrying ability, and fatigue resistance. Clean surface after treatment.
	Steering arm bushings. Valve rocker arms. Valve rocker arm shafts. Gear shifter shafts. Brake and clutch pedal shafts. Water pump shafts.	Generally semifinished before treatment and finish-ground after treatment.	Enough case to permit finish grinding and maintain high hardness for necessary wear resistance.		
0.040″ to 0.060″	Ring gears. Drive pinions. Transmission gears. Side gears. Side pinions.	Finished before treatment except for lapping operation.	High wear resistance to resist sliding, rolling, or friction of abrasive nature. Resistance to heavy crushing. Resistance to high alternate bending stresses.		
	Piston pins. Steering knuckle pins. Side pinion axles. Reverse idler gear shafts. Counter gear shafts.	Semifinished before treatment. Finish-ground after treatment.	Operate frequently in bronze bushings. High wear resistance. Resistance to relatively high unit loads that cause Brinelling. Resistance to fairly high alternate bending stresses. King pins also require resistance to high instantaneous or shock loads.		
	Roller bearings.		Resistance to heavy rolling action.		
Over 0.060″	Camshafts.	Semifinished before treatment.	High wear resistance. Resistance to shock. Resistance to relatively high unit loads with a rapid sliding action.		

ASM Handbook (1942 ed.). As service becomes more severe as in trucks and buses, the depth of case for corresponding parts may be somewhat deeper, and the general tendency is to change to a steel which permits better physical properties, especially in the core.

TABLE 10–9

Observed Flame Hardness of Various Steels*

Approximate SAE Specification	C	Mn	P	S	Si	Cr	Ni	Mo	Va	Brinell Hardness	
										Compressed Air-Quench	Water-Quench
X1335	0.35	1.45	....	....	....	....	....	....	....	....	500
1040	0.35	0.80	0.04	0.03	0.30	....	....	....	....	....	444
1045	0.45	0.75	0.04	0.05	....	....	....	....	....	....	555
1055	0.55	0.74	0.02	0.04	0.22	....	....	....	....	....	712
1095	1.00	0.30	0.02	0.02	....	....	....	....	....	....	700†
51210	0.12	Forging Rolled Stock			....	13.00	....	....	....	444	....
51210	0.12				....	13.00	....	....	....	....	444
....	1.25	0.20	....	....	....	0.50	....	....	....	....	614†
3140	0.40	0.80	....	....	....	0.60	1.25	....	....	....	540
2330	0.30	0.68	0.02	0.03	....	....	3.48	....	....	....	600
								0.25	....	415	....
4140	0.40	0.80	....	....	....	0.95	....	0.20	....	....	525
4140	0.40	0.80	....	....	....	0.95	....	0.20	....	375	....
	0.68	0.75	0.02	0.03	0.22	....	....	0.34	....	....	712
	0.90	....	....	....	....	....	....	....	0.25	....	725
6140	0.40	0.75	0.03	0.04	....	0.95	....	....	0.17	500	....

* *Welding Handbook* (1942 ed.), American Welding Society, New York

† Very mild quench by water.

TABLE 10–10

Observed Flame Hardness of Cast-Irons*

Type	Total C	Combined C	Si	Mn	P	S	Ni	Cr	Mo	Brinell Hardness Water-Quench
Gray	3.46	0.76	1.58	0.76	0.144	0.083	....	.....	....	540–600
Gray	3.44	0.69	1.51	0.87	0.194	0.087	....	.....	....	550–610
Gray	3.44	0.77	1.70	0.75	0.300	0.085	....	.....	....	550–615
Meehanite A	2.97	0.66	1.62	0.78	.....	.....	Nil	0.045	....	500–605
Meehanite C	3.04	0.68	1.65	0.79	.....	.....	Nil	0.045	....	500–620
Gray	3.22	0.65	1.73	0.75	0.212	0.089	....	.....	0.47	560–635
Gray	3.15	0.70	2.00	0.90	.....	.....	1.37	.....	....	525–575
Gray	3.30	0.73	1.34	....	.....	.....	1.43	.....	0.85	550–605
Gray	3.19	0.84	1.22	....	.....	.....	1.11	0.10	0.76	550–605
Gray	2.87	0.84	1.87	....	.....	.....	0.18	0.21	....	560–610

* *Welding Handbook* (1942 ed.), American Welding Society, New York.

10–29. Induction Heating. Another process for obtaining a hard surface on hardenable steels involves the placing of the part within a magnetic field, set up by inductor blocks carrying an electric current of high or low frequencies, as shown in Fig. 10–27. A steel part placed within such a field is heated very rapidly, principally on the surface, to a depth of a few thousandths of an inch, by hysteresis or frictional molecular action and by eddy currents induced in the work piece. After heating above the critical temperature when the steel becomes practically non-magnetic, the heating resulting from hysteresis ceases and the part is quickly quenched with a water spray while it is still in place.

The process is adaptable for heating a part deeply, or throughout, or on its surface. The depth of heat penetration varies inversely as the frequency of current pulsations. For heating bars for forging, ordinary power frequencies of 60 cycles may be used, though frequencies of 1,000 to 2,000 cycles are more common. However, for surface-hardening, extensive use is made of current ranging from 3,000 to 400,000 cycles and even higher.

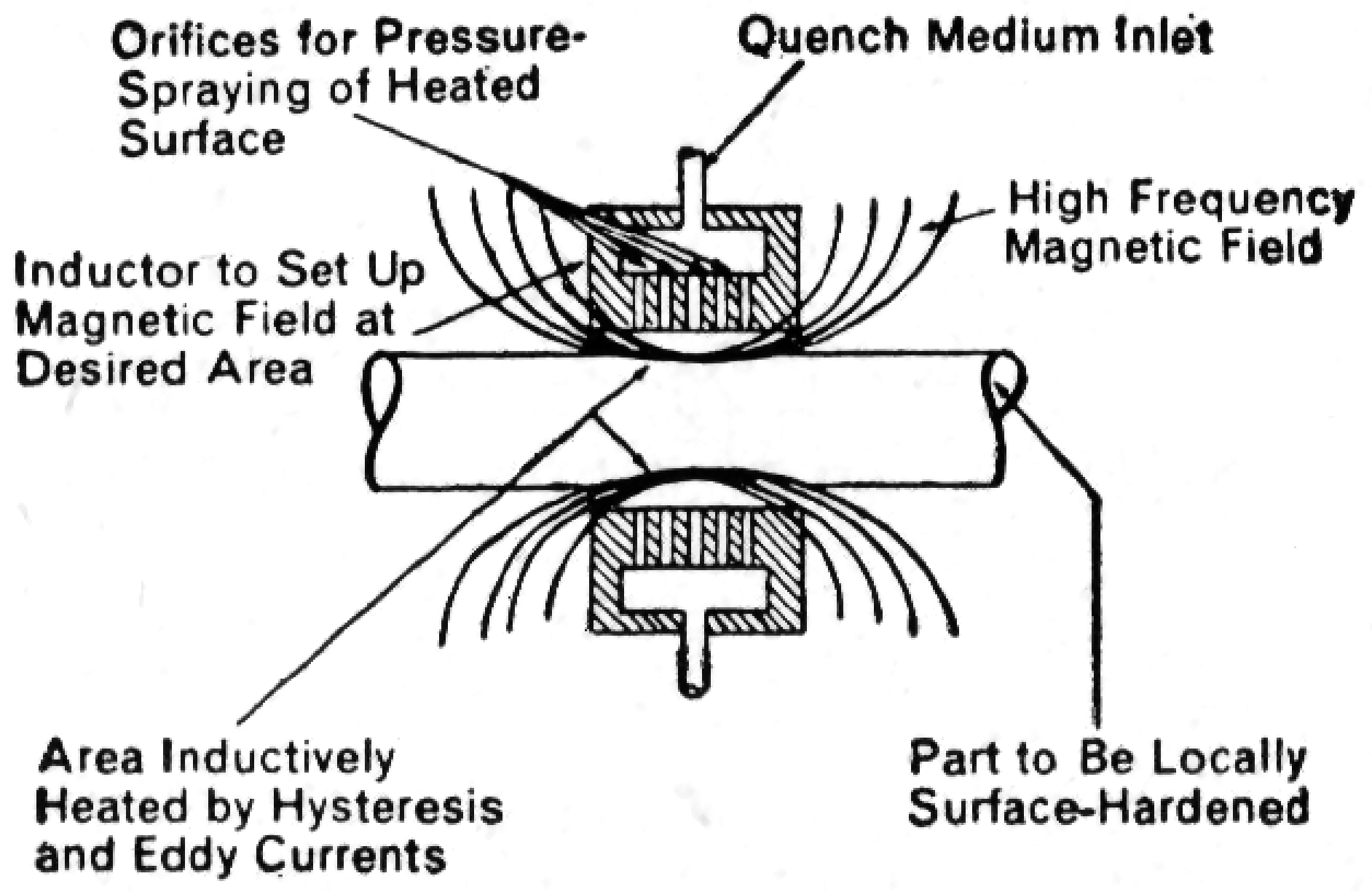

Orifices for Pressure-Spraying of Heated Surface
Quench Medium Inlet
High Frequency Magnetic Field
Inductor to Set Up Magnetic Field at Desired Area
Area Inductively Heated by Hysteresis and Eddy Currents
Part to Be Locally Surface-Hardened

Fig. 10–27. Position of induction blocks for heating a localized area. (Courtesy of Ohio Crankshaft Co., Cleveland, Ohio.)

As the heating action is confined to the surface layers of metal, the original core properties are retained while the surface may, upon rapid cooling, be hardened in a manner similar to carburizing.

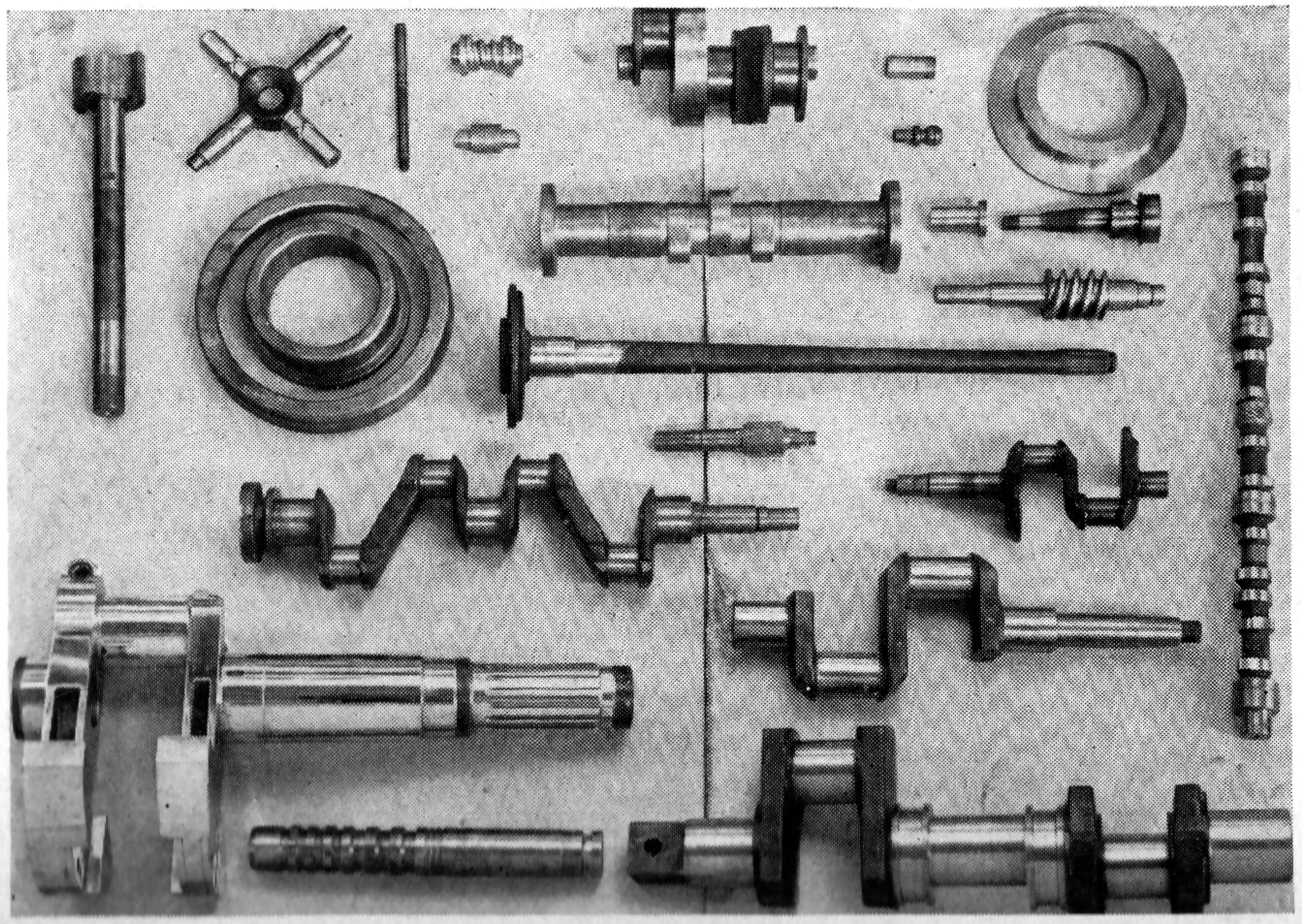


Fig. 10–28. Some engine parts suitable for induction hardening. (Courtesy of Ohio Crankshaft Co., Cleveland, Ohio.)

The advantages of induction heating include (1) extremely high production because of very rapid heating; only a few seconds are required to heat a 2½-in. crankshaft bearing on the surface, (2) no warpage, since only the localized section that is needed hard is heated, (3) complete automatic control of heating and quenching, and (4) improved working conditions. Fig. 10–28 shows parts suitable for induction hardening. Fig. 10–29 shows a macrostructure of an induction hardened 4-in. crankpin bearing made of SAE 1050, which has a hardness of 55 Rockwell C.

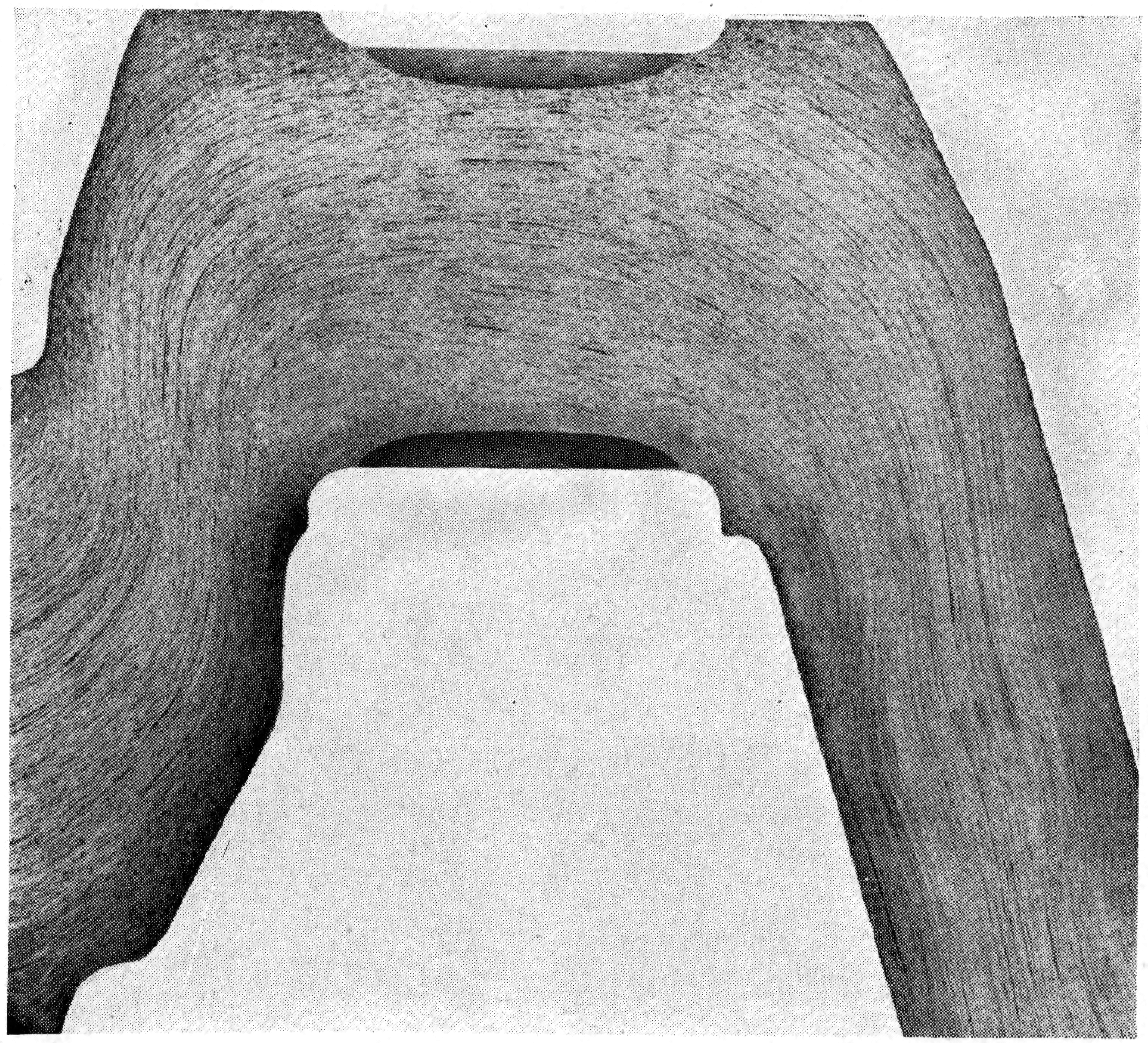


FIG. 10–29. Induction hardened crankpin. (Courtesy of Ohio Crankshaft Co., Cleveland, Ohio.)

10–30. Temperature Measuring Devices. The emphasis placed on correct temperature in the making of steel and in its subsequent shaping and processing necessitates the use of devices for either indicating or recording high temperatures accurately. Mercury thermometers are unsuited except for relatively low temperatures such as used in oil tempering. Instruments used for the measurement of high temperatures

employ principles whereby temperatures may be measured either by the intensity of radiation (measuring the resistance of a coil of wire at the furnace temperature) or by means of a current flow within a circuit consisting of two dissimilar metals joined together (called *thermocouple*) and connected to a proper instrument for measuring it, such as a millivoltmeter or potentiometer.

In steelmaking processes, the customary method of checking on temperatures has been by means of optical pyrometers, in which the brightness of the interior of the furnace is compared to a standard source of light or filament whose resistance is known. Much more accurate means, consisting of the immersion of thermocouples in the molten metal, are now used. Couples which must be fully protected against slags and gases have the disadvantage that readings cannot be made quickly enough, since the heat must penetrate the protecting sheaths. However, recent use of thermocouples made of carbon-silicon carbide and tungsten-graphite indicate that readings may be made in 7 to 10 sec, since the couples may be inserted into molten metal unprotected; readings up to 3300F have been made.

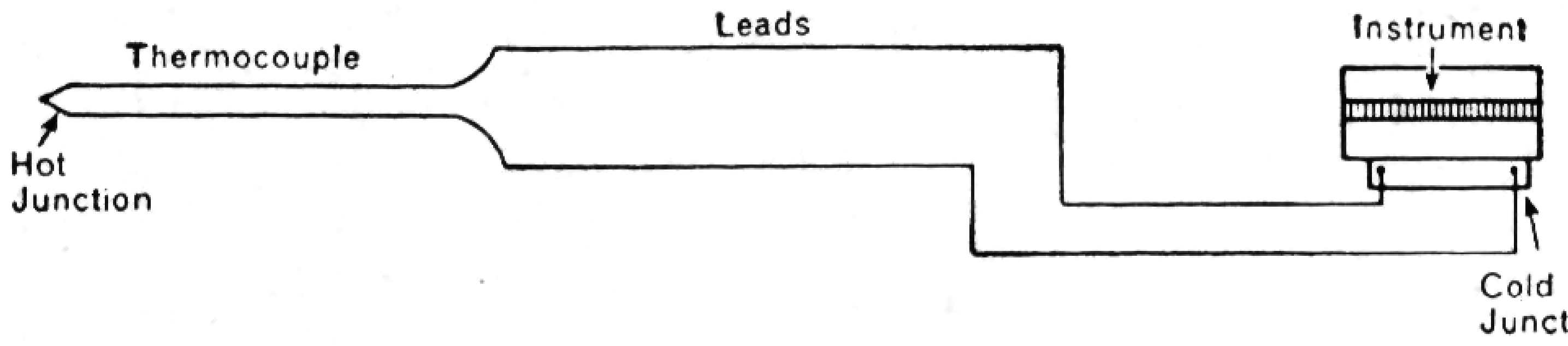


FIG. 10–30. Thermoelectric device for indicating temperature.

The thermoelectric method, however, provides the most satisfactory means of determining temperatures for forging and heat-treating steels and other metals. The principle of this device is that when two dissimilar metals are joined at one end and heated while the other ends, connected to a millivoltmeter or potentiometer, are held at a constant temperature, a current or potential is set up in the circuit whose magnitude is approximately proportional to the difference between the hot and the cold junctions. As the maximum potential or electromotive force (emf) produced is only about 50 millivolts maximum, sensitive instruments are required to record it. Thermocouple circuits also require careful handling and clean, dry locations; and all contacts must be secure.

Thermocouples are attached to the meters through flexible lead (not Pb) wires. A simple circuit is shown in Fig. 10–30, and its application is shown in Fig. 10–31.

A thermocouple suitable for measuring temperatures up to 2800F is made of pure platinum and an alloy of platinum and 10 per cent rhodium. Its disadvantages are that it is expensive, gives a very small emf, and must be fully protected against reducing furnace atmospheres.

Base metals adapted for measuring temperatures to a maximum of 2000F are copper + copper-nickel alloy for temperatures up to 700F; iron + copper-nickel alloy up to 1200F; nickel + chromium + copper-nickel alloys up to 1400F; nickel-chromium alloy + nickel up to 1800F; nickel-chromium + nickel-aluminum alloy up to 2000F.

Because small temperature changes make for a larger deviation of the indicator, thus permitting more accurate readings, and since recordings are independent of electrical resistance in a part of the circuit, potentiometer-type instruments are preferable to the millivoltmeter type for measuring the emf.

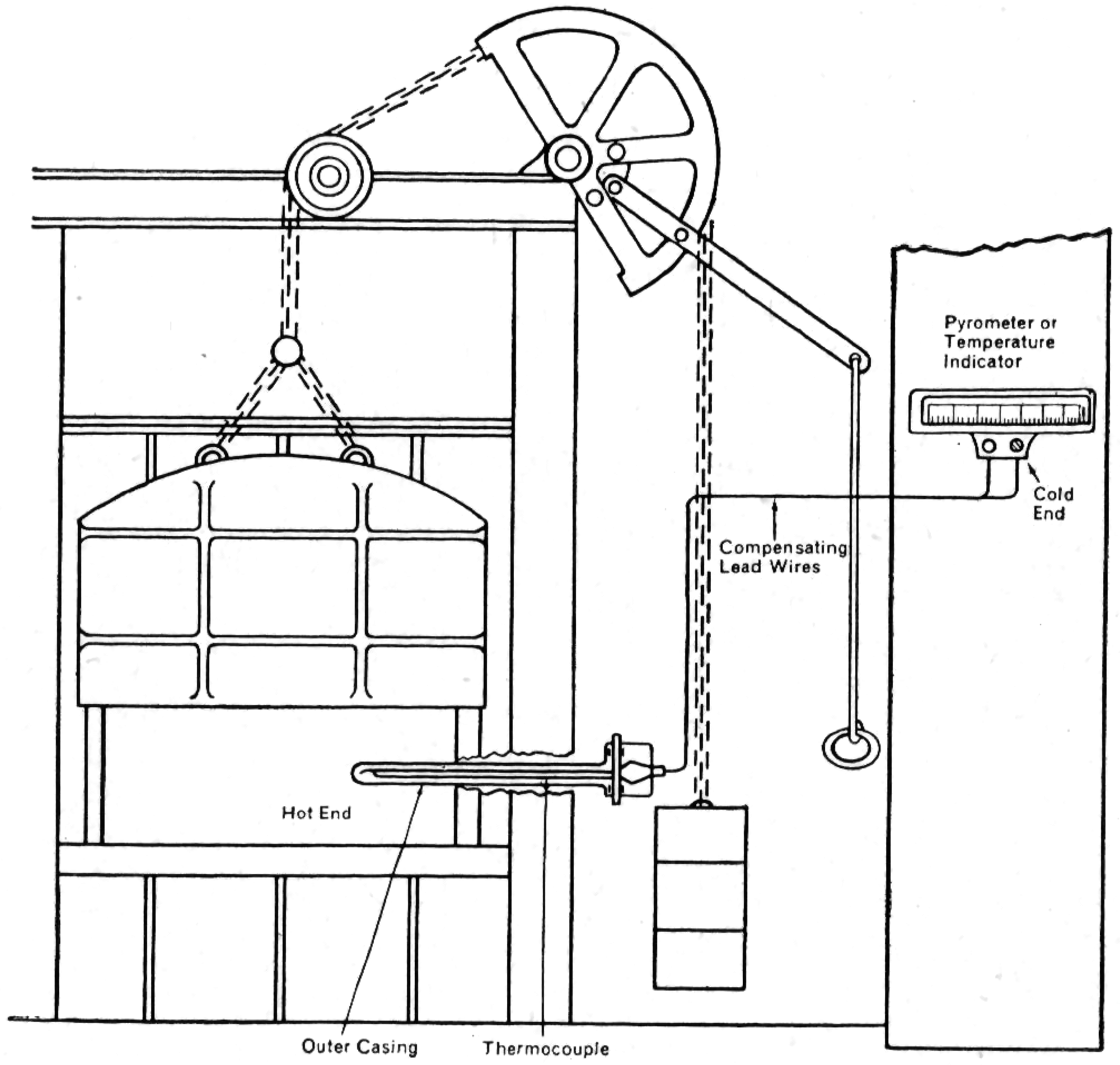


FIG. 10–31. Installation showing location of thermocouple in furnace, and manner of connecting to pyrometer.

Complementing the measuring devices, a continuous record of furnace temperature is plotted automatically on a roll of graph paper for the permanent record of production.

QUESTIONS AND PROBLEMS

1. Summarize the influence on the mechanical properties of the various heat-treating processes.
2. Define "process annealing" and "patenting."
3. Is a slow cooling rate essential in the annealing of all metals?
4. Discuss the fundamentals of the heat treatment of steels.

5. In what forms may pearlite be found in steels? Explain how each may be produced.
6. What phase of steel exists above the Ac_3 temperature?
7. What microstructures are present at normal temperatures in a 0.75 per cent C steel cooled at the following relative rates: (1) very slowly, (2) moderately slowly, (3) moderately fast, (4) very rapidly.
8. Classify troosite, pearlite, martensite, sorbite, and austenite as to plasticity, hardness, tensile strength, impact strength, reduction of area, and elongation.
9. What is the influence of cooling rate on the stability of austenite?
10. Explain the mechanism of the hardening of steel by quenching in oil and water.
11. What is the influence of the mass of a steel quenched from the critical temperature on the impact toughness?
12. Assume an alloy and a plain C steel of equal volume with a low and a high critical cooling speed, respectively. Which of the two hardens to the greater depth by quenching from their respective critical temperature?
13. List the factors influencing hardenability.
14. Which element in steels is most potent in determining hardness?
15. Discuss the objectives of tempering.
16. Discuss in detail the metallurgical results of tempering.
17. Explain the mechanism of austempering.
18. How does the Jominy end-quench test form a basis of determining hardenability of steels of various diameters?
19. Discuss the significance of grain size.
20. Compare the various casehardening processes as to cost, time, steels, depth of case, and application.
21. Define and discuss the significance of critical cooling speeds.
22. Give the chemistry of nitriding and cyaniding.
23. What is the chemistry of the surface hardening of gray and malleable cast-iron by the oxyacetylene process?
24. What subsequent heat treatment is best suited for SAE 1015 carburized parts requiring high impact strength?
25. What type of metals are best suited for thermocouples?
26. What means are most commonly used for measuring temperatures for heat-treating metals?

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CHAPTER 11

THE MECHANICAL WORKING OF METALS

11–1. Introduction. All commercial ferrous and nonferrous metals and alloys are ultimately used in either the cast or wrought form. Of the nearly 90,000,000 gross tons of iron and steel produced in the United States annually, the incomparably larger proportion consists of plates, wire, sheets, and rails; structural shapes such as angles, channels, I-beams, T-bars; round, square, rectangular, or octagonal shapes known as merchant bars; and such products as crankshafts, connecting rods, axles, steering knuckles, and numerous other forgings for ships, planes, locomotives, automobiles, cranes, and excavators—all of which are the result of mechanical working.

All metals in the *as-cast* condition are generally inferior in mechanical properties to metals of comparable analysis in wrought form. Therefore, parts required to withstand more severe service stresses, both static and dynamic, than is obtainable with cast metals are preferentially made of metals that have been mechanically worked in the hot plastic state by the pressure of rotating rolls, by the squeeze of hydraulic or mechanical presses, or by the impact of large steam- or air-operated hammers, described later.

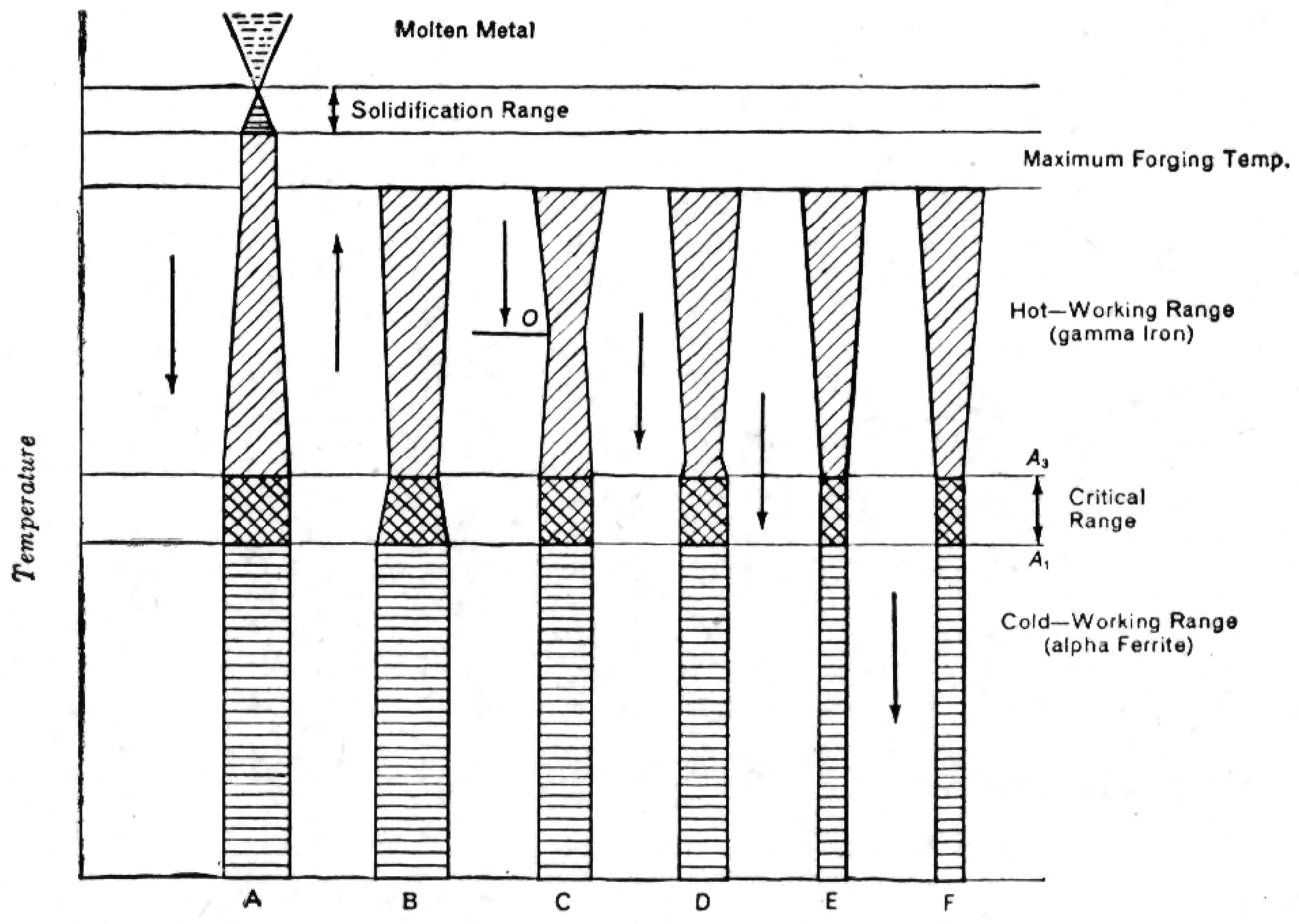
The small and simple forgings, made individually with the aid of a hammer and sledge and a few simple tools by the smith on his anvil, stand in striking contrast to those forgings which are produced today at astounding rates by massive machines of a multitude of shapes, weights, and degrees of difficulty. The engineer's skill in modern forge production is vastly more important than the smith's physical stamina; and the forging equipment now ranks as machine tools, because the products compare in precision with those in other lines of production.

11–2. Influence of Mechanical Working. The plastic working of the cast structure of an ingot of steel by rolling or squeezing eliminates its coarsely grained and heterogeneous structure; it also causes cavities in low-carbon (weldable) steels to become welded and closes up those in higher-carbon and alloy steels. A general increase in mechanical properties is effected, with a more pronounced improvement in a plane parallel with the longitudinal axis or in the direction of working.

Primarily, the most important reasons for forging or working a metal are (1) to produce a part of a desired size and shape, and (2) to obtain improved mechanical properties through the refinement of grain structure.

Regardless of which process the metals are worked by and at which plastic working temperatures, respectively, the applied force breaks up the coarse austenitic grain structure by producing slip along crystallographic planes, with a consequent fragmentation of the original grain and the birth of new and smaller grains.

The extent to which the grain size is reduced by forging varies directly as (1) the amount of mechanical working the metal receives, (2) the final temperature range at which the work is carried out, and (3) the original grain size. The maximum advantages are obtained when the working of the metal is continued to the lower limits of the critical range shown in the schematic diagram in Fig. 11–1. This is known as a critical temperature partly because conditions which prevail in the metal at this temperature remain without change; whereas, if forging is discontinued at higher temperatures, its effects are effaced by the ability of the metal to recrystallize or *anneal* itself.



A and B. The influence of slow cooling and reheating to working temperature are shown.
C. Hot-working to O reduces grain size. Self annealing causes slight grain growth.
D. Hot-working is continued to A_3 temperature.
E. The working is carried out to A_1 temperature and results in maximum grain refinement. No grain growth below the A_1.
F. Working below the A_1 (cold-work) effects grain orientation. No grain refinement.

FIG. 11–1. Relation of cooling rate and hot mechanical working to the grain size of a medium-carbon steel.

11–3. Malleability of Steel.

Malleability, or the ability to withstand permanent changes in external shape by plastic deformation in the hot or cold state, constitutes one of the most important properties of metals. Because of their heterogeneity or because of the presence of a brittle phase or constituent, some metals break under any stress tending to produce deformation. Others may be forged to a limited extent or within a certain temperature range. The low- and medium-carbon steels forge readily and without difficulty, while higher-carbon and some alloy steels, though forgeable, require greater care. In addition to the steels, many other metals and alloys—such as aluminum, copper, brass, bronze, magnesium, and monel—are also capable of plastic deformation in both the hot and cold state, as discussed in Chapter 8.

When a metal is compressed by a blow or a squeeze, its length or width or both increase in direct proportion to the reduction in its thickness. In other words, the metal is subjected to a three-dimensional or triaxial stress, as shown in Fig. 11–2. It must withstand this stress if permanent deformation is to be effected.

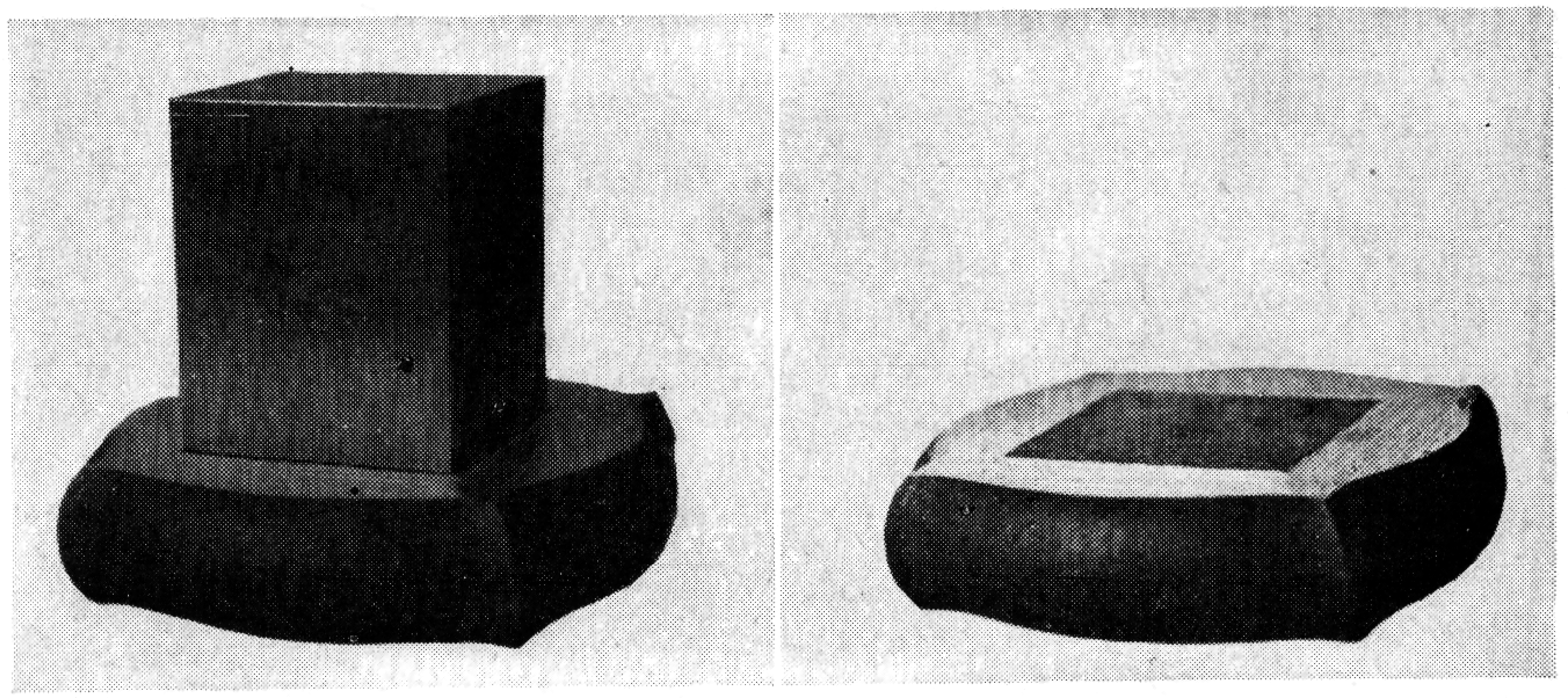


FIG. 11–2. Influence of a force applied parallel with axial length of bar of metal, an operation called upsetting.

The principal factors affecting the forging quality of a metal are its chemical composition, its surface condition, its crystalline structure, and its ability to *flow* freely in all directions without rupture under either pressure or impact.

11–4. Forging Operations.

The principal forging operations are those which (1) produce an increase in the cross-sectional area in proportion to the reduction in length or thickness, known as upsetting, shown in Figs. 11–3, 4, and 5; and those which (2) draw out or lengthen, as exemplified by a bar or billet being reduced in diameter or an ingot being converted into a plate or shaft by rolling or pressing. Some forgings may be the product of only one of these operations, but, as a study of the following examples clearly shows, the larger proportion calls for several operations for their completion.

11–5. Fiber Flow.

Although the cast structure no longer exists after a steel ingot has been hot-forged, results of its dendritic structure persist even after it has been reduced to the smallest bars; and control over these results constitutes a factor of major importance in the production of high quality forged steel shapes.

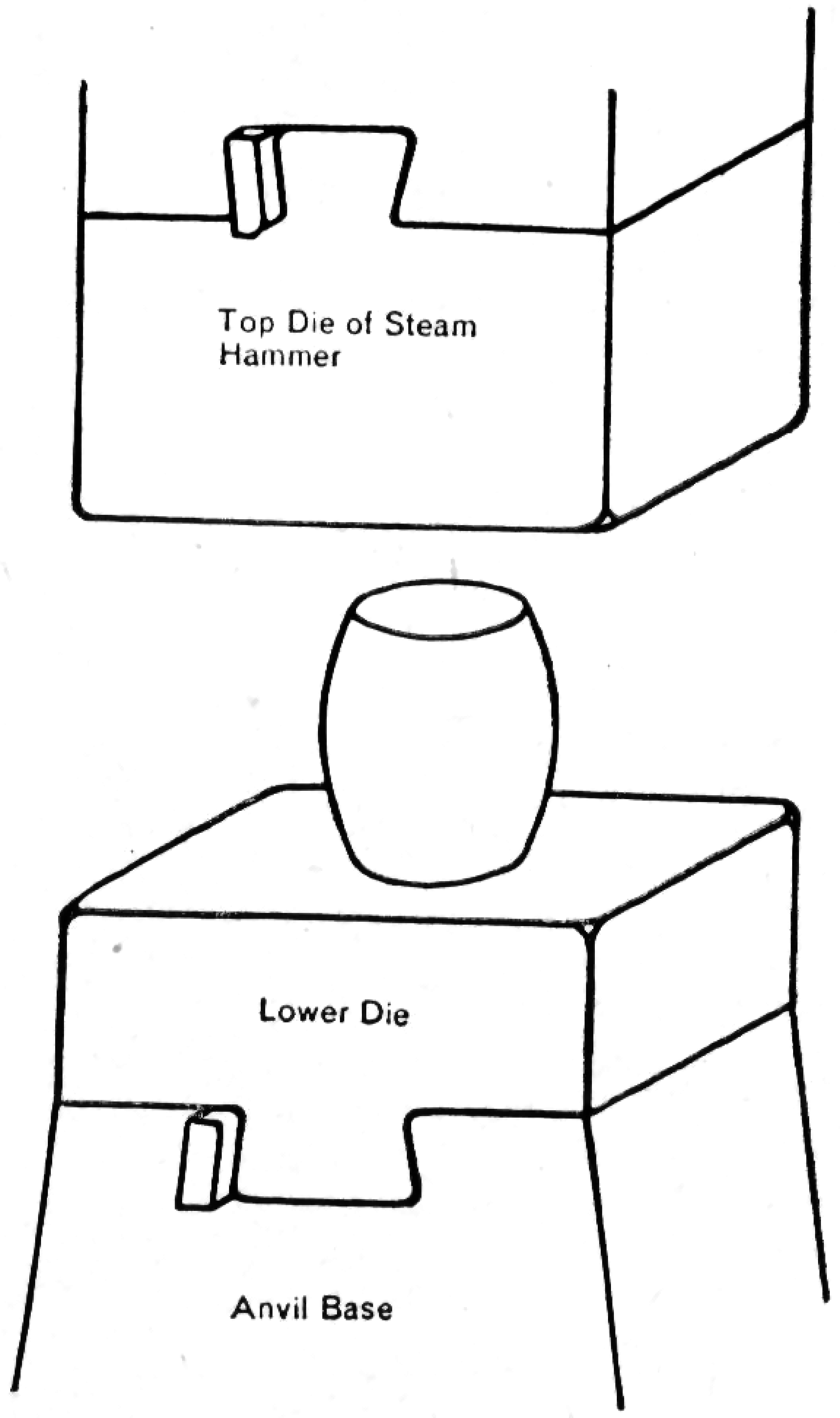

Top Die of Steam Hammer
Lower Die
Anvil Base

Fig. 11-3. Upsetting a short cylinder under a steam hammer.

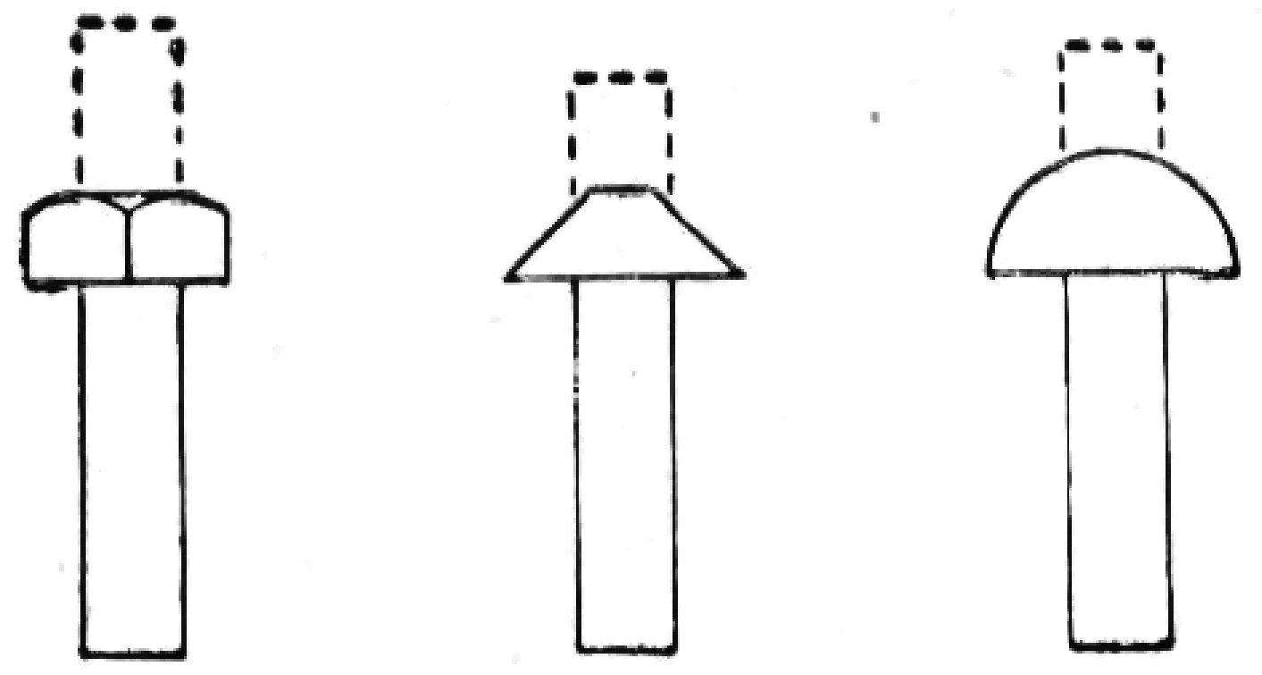


Fig. 11-4. Bolt and Rivet heads produced by upsetting in a forging machine.

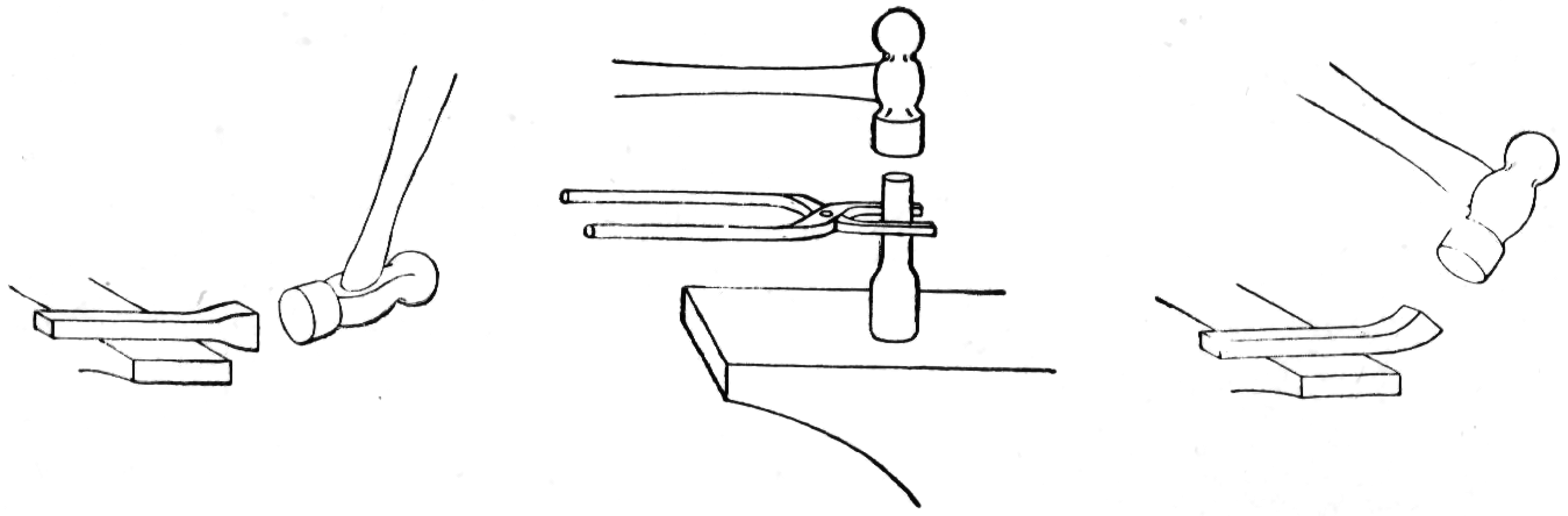


Fig. 11-5. Three methods of upsetting small bars on the anvil with a hand hammer.

As pointed out in Chapter 5, cast metals have no directional properties; this is revealed by the practically identical tensile values that can be obtained with test bars cut from all axes. As an ingot is forged, however, its dendritic structure becomes definitely orientated or lengthened in the direction of metal flow, or parallel with its axis. Thus, when a bar reduced from such an ingot is sectioned and immersed in a solution consisting of 50 per cent hydrochloric acid and water heated to about 150F for a few minutes, it reveals a fiber or grain flow pattern similar to that of wood.

However, steel is not wholly analogous to wood in its fibrous structure, because steel is crystalline and its grains are equiaxial; yet, like wood, the strength and toughness of steel in a plane parallel to the fiber flow are greater than in a plane transverse to it. In view of this, the distortion of the fiber should follow the general contour of the finished forging, and the *flow* lines should be in the direction of the greatest required strength. Examples of this are given in Fig. 11-6 at (*a*), where a cylinder of steel is shown upset or up-ended into a gear blank so that the fiber of the metal forms a radial pattern. Teeth in this blank will have the fiber running

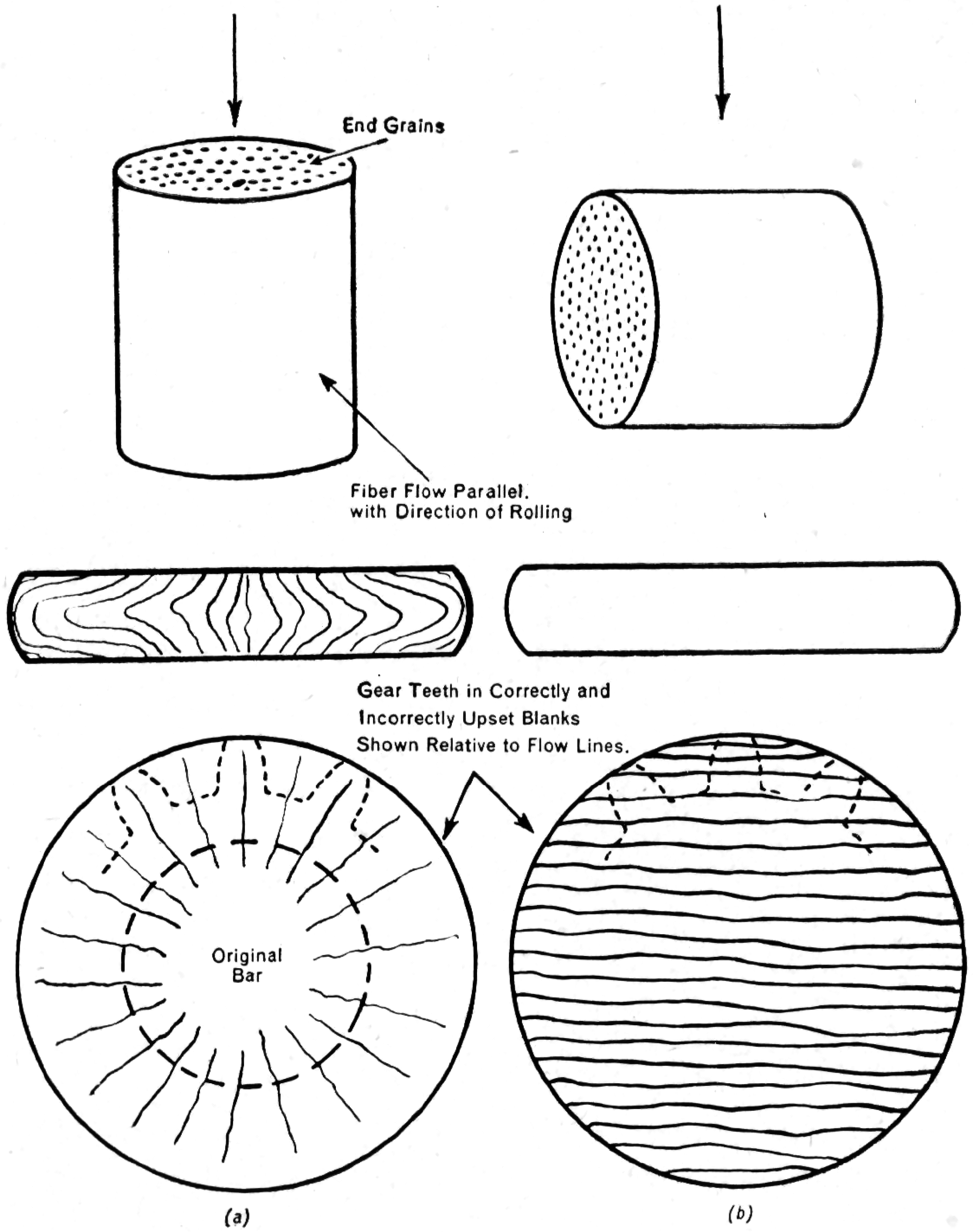

End Grains
Fiber Flow Parallel. with Direction of Rolling
Gear Teeth in Correctly and Incorrectly Upset Blanks Shown Relative to Flow Lines.
Original Bar
(a)
(b)

Fig. 11-6. Correct (*a*) and incorrect (*b*) method of upsetting gear blanks for maximum strength and wear resistance.

transverse with the direction of stress in each tooth, thus imparting the maximum resistance to shear and wear. Fig. 11–6 at (*b*) shows a gear blank where the fibers run in an almost horizontal direction, so that in one half of the gear teeth the fibers follow a plane parallel with the applied load, a plane in which the teeth will have a greater tendency to fail in shear.

As it is poor engineering practice to design a part in which a stress becomes highly concentrated during service conditions, care must be taken to avoid the presence of end grains too near the surface in critical sections of forgings. Such end grains become areas of high local stress concentration and will, under service conditions, eventually cause a gradual but progressive failure of the part through that section. Examples of correct forging techniques are exemplified by the distribution of the flow lines in the crankshafts shown in Figs. 11–7A and 11–7B. The factors of most importance in controlling the flow lines are (a) forging temperature, (b) forging procedure, and (c) die design.

11–6. Heating of Forgings. By far the most common method of producing forgings is manipulating them at elevated temperatures. This is known as *hot-working,* as differentiated from *cold-working* the metals at ordinary temperatures, as described later. Consequently, the manner and extent of heating the metal preparatory to forging becomes a factor hardly less important than the subsequent working of the metal, if desirable results are to be attained. It should, therefore, be undertaken with a view to heating economically, uniformly, and to the correct temperature for each grade of metal. Increasing emphasis is placed on correct furnace atmosphere, one of the more important factors involved in proper heating, in order to avoid excessive oxidation or scaling and, in some instances, loss of some of the constituents of the metal. This is particularly true of steel when it is heated to a high temperature under oxidizing conditions. The reaction, or scaling, which occurs results in the loss of the carbon on the surface and produces a condition known as *decarburization.* On forgings which require subsequent heat treatment, such as hardening, this is undesirable. Overheating and prolonged exposure at high temperatures of some steels also produce excessive growth of the grains and, particularly under oxidizing furnace conditions, tend to destroy the intercrystalline cohesion, thus rendering the metal useless for further service. This is commonly called *burning.* The structure of overheated steel may be restored by normalizing or mechanical working, but a *burnt* steel must be discarded.

Forging at either too low or too high a temperature or forging a nonuniformly heated steel may produce serious and often hidden defects. Therefore, for successful forging, the metal should be heated to the correct temperature and allowed just sufficient time to absorb the heat uniformly.

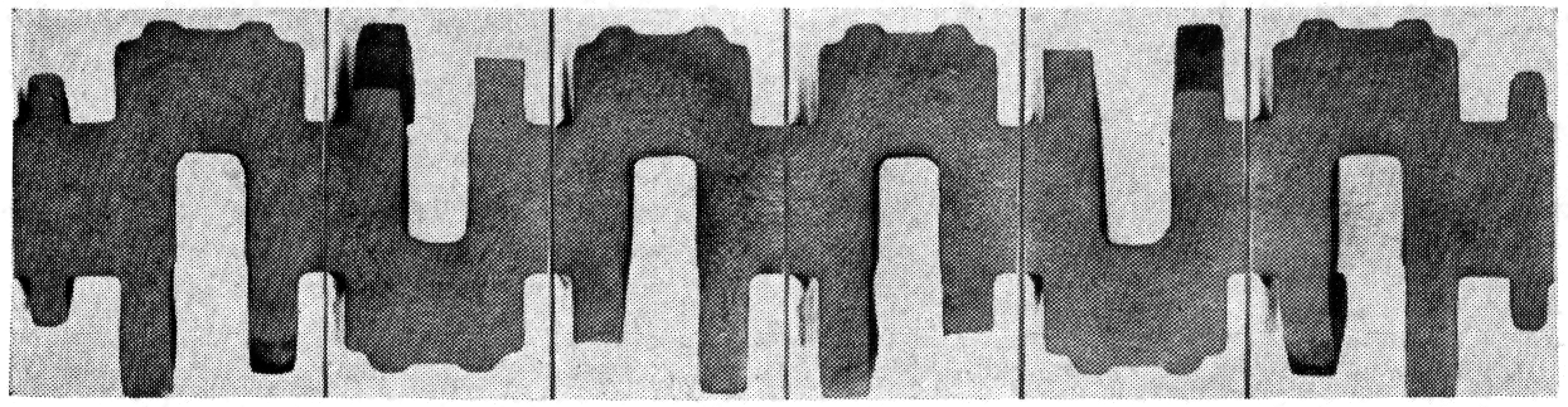


Fig. 11–7A. A six-throw, seven-bearing crankshaft forging, showing correctly positioned flow lines. Approximately 1/10 actual size. (Courtesy of Wyman-Gordon Co., Harvey, Illinois.)

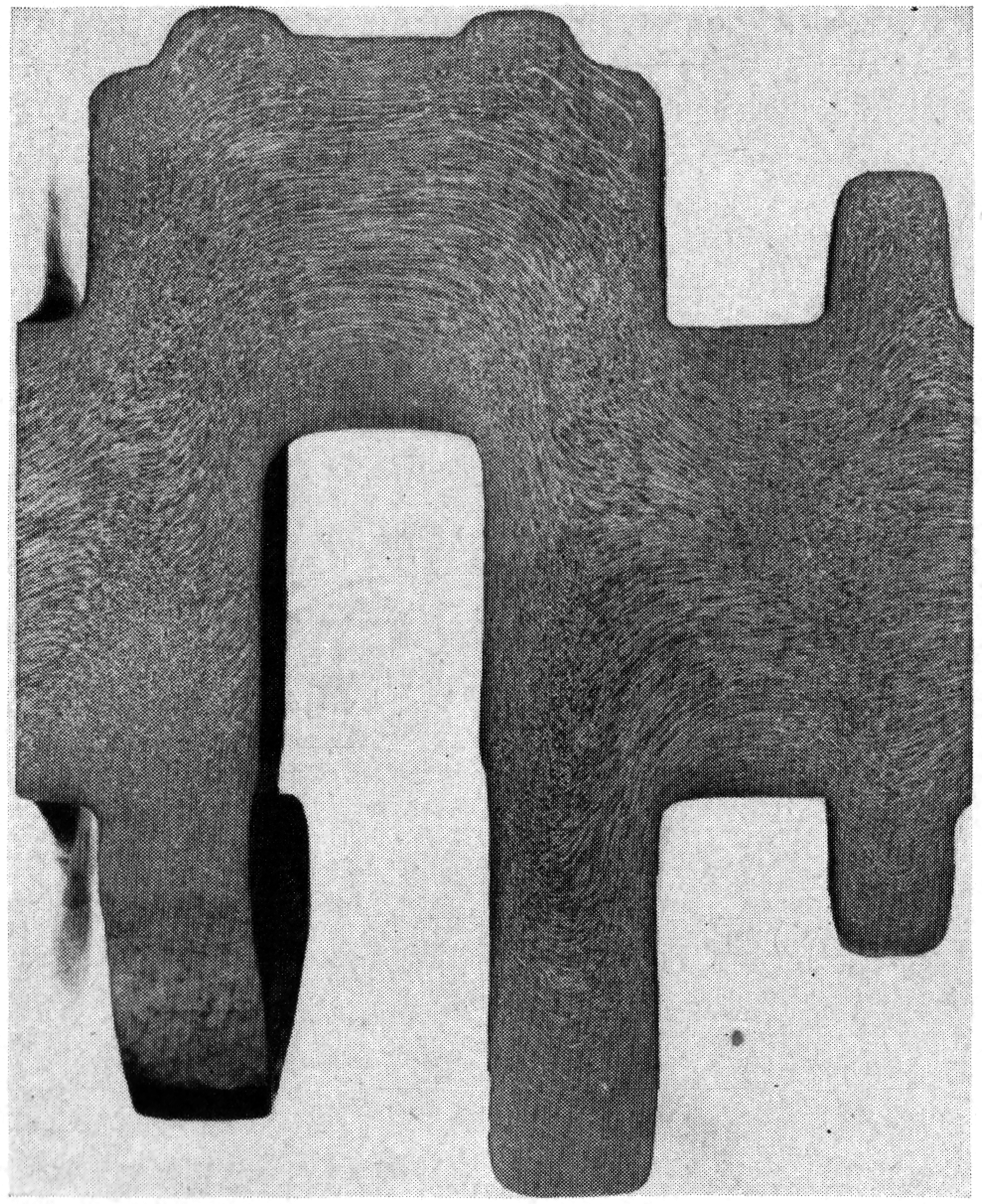


Fig. 11–7B. Flow lines in section of forged steel crankshaft. Approximately half size. (Courtesy of Wyman-Gordon Co., Harvey, Illinois.)

11–7. Heating Time. The heating rate of steels of the same analyses varies directly as their thickness or diameter. Low-carbon steels, 0.50 per cent carbon and less, are heated in a slightly shorter time than are either higher-carbon or alloy steels where the heat diffusivity (conductivity/density) is lower. Up to 3 in. in diameter, plain low-carbon steels are heated in a minimum time of about 5 min for each inch of diameter or thickness, while larger thicknesses require a proportionately longer time. The laws of the transmission and conduction of heat within a body make it inadvisable to apply heat too rapidly to cold steel of a large cross-section. It is known that high thermal gradients, produced by the concentration of heat at the surface, cause stresses of sufficient magnitude to burst steel parts of large cross-section.

Specifically, the heating of a steel of a known analysis involves two distinct considerations—one associated with the heating of small bars and the other with the heating of large masses. Small bars are usually considered as those whose diameter or thickness is less than 4 in.; they require only that the heat be applied to their surface, its distribution within the metal being considered of no serious importance. Such bars are, therefore, exposed evenly to the source of heat in the furnace. Steel of larger diameter, on the other hand, requires not only that heat be applied to the surface, but also that there be uniform diffusion within the metal also. The heating rate, therefore, must be conditioned by the ability of the surface to absorb heat and also by the thermal conductivity of the metal. When the size and the shape of a metal are similar, the heating time will vary inversely as its specific heat throughout the range to which it is heated.

In addition to the size and the analysis, the shape is also an important factor in heating. When the ratio between the exposed surface and the diameter is large, less time will be required to heat than when this is relatively small. For example, the ratio of the surface of a plate to its volume is equal to 2 over the diameter or thickness ($2/D$); that of a cylindrical or square bar equals 4 over the diameter ($4/D$); and that of a sphere equals 6 over the diameter ($6/D$). Since the constants of each equation are in the ratio of 1:2:3, the heating time of parts of these geometric shapes, when the thickness or diameter and the analysis are similar, will vary inversely as these ratios, or as 3:2:1.

Invariably, quantity production of forgings of small and medium weights, as well as the heating of large ingots, is done in furnaces heated by oils, gases, powdered coal, or electricity. The most commonly used of these fuels are crude and distillate oils, with various available gases next. Not many forging furnaces utilize electricity as a source of heat.

The most common types of furnaces are: those known as *batch* type, in which the material is placed on the hearth and removed through a counterweighted door; the *end heating* type for heating the ends of bars; the continuous operating or *pusher* type, in which the material is placed at one end and is then slowly moved toward the opposite end where there is a door for its removal; and the *rotating hearth*. Usually the heating chambers of all these furnaces provide for heating the materials either by contact with the hot gases or by radiated heat, or by both. A typical forging furnace is shown in Fig. 11–8.

11–8. Forging Temperature. Since the plasticity of a metal in the forging range increases directly as the temperature, production rates demand that the maximum temperature the metal will stand without injury be employed, in order to reduce the time and the energy spent in producing a desired shape. In the making of duplicate forgings with the aid of dies, not only does the metal flow more easily to fill the various impressions when higher temperatures are used, but also die life is greatly increased because of less wear.

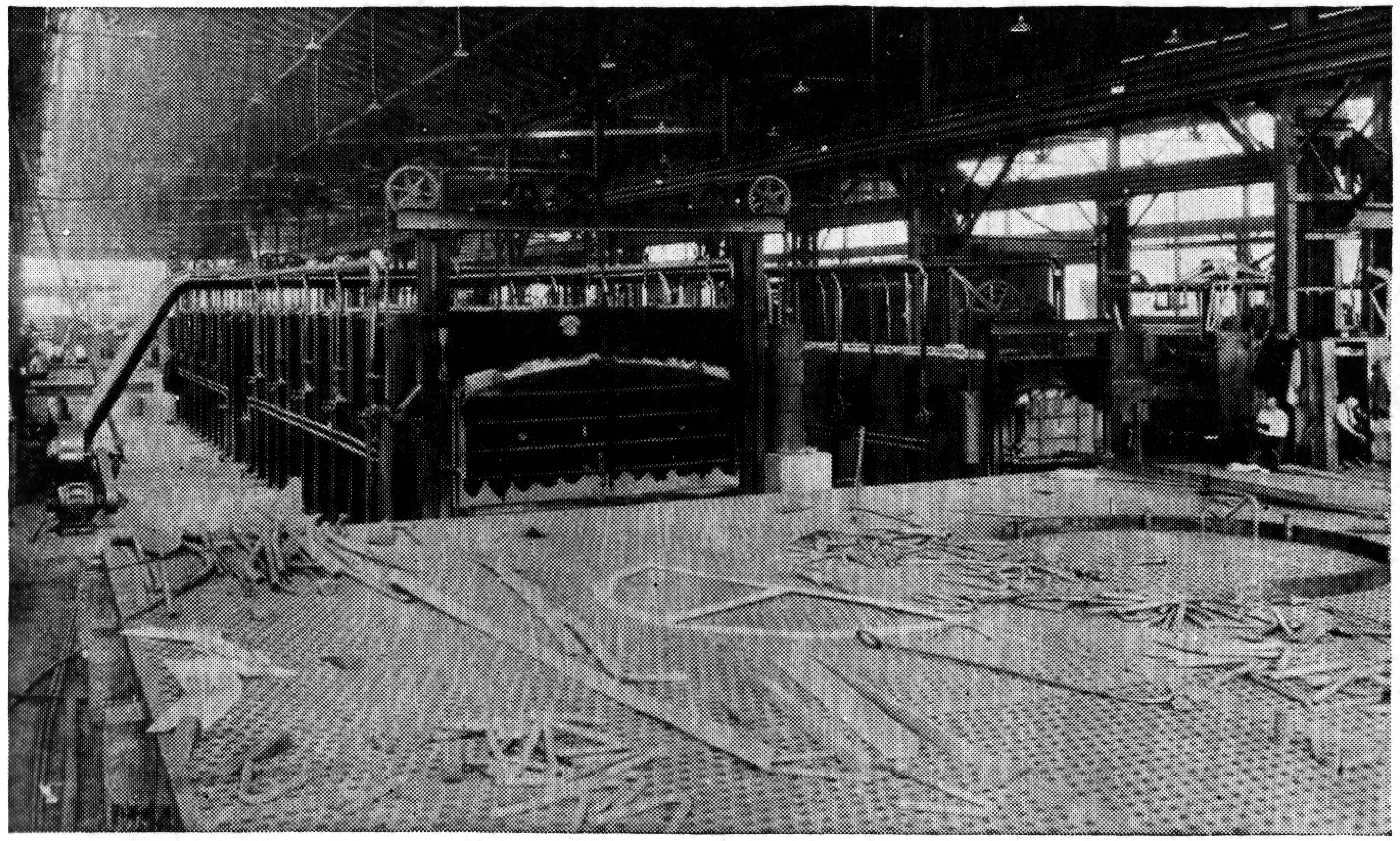


FIG. 11–8. Plate and angle furnace of type commonly used in shipyards; forming plates and clamps are shown in foreground. (Courtesy of W. S. Rockwell Company, New York.)

As pointed out in Chapter 9, carbon is the most important constituent of plain carbon steels; it not only lowers the maximum forging temperature, but it also increases the static resistance to plastic deformation. The influence of carbon on the forging temperature is shown in Table 11–1, where the maximum forging temperatures with reducing furnace atmospheres are given for steels of various carbon analyses.

Where drastic deformation of the metal is contemplated, the usual commercial practice is to employ maximum temperatures no less than 200F below that of the incipient fusion of the metal. Alloy steels have a forging range from about 2100F to 2300F, depending on the alloy and its amount.

TABLE 11–1

INFLUENCE OF CARBON ON FORGING TEMPERATURE OF STEEL

SAE No.	Carbon (Per Cent)	Forging Temp. (F)
1015	0.10–0.20	2400
1020	0.15–0.25	2350
1030	0.25–0.35	2320
1040	0.35–0.45	2280
1050	0.50–0.60	2220
1060	0.55–0.70	2160
1070	0.65–0.70	2100
1080	0.75–0.90	2050
1090	0.85–1.00	2020

11–9. Forging Procedure. In order to produce forgings free from defects, considerable importance is attached to the sequence in which the section is reduced; therefore, approved procedures are carefully followed, and dubious ones are as carefully avoided. Fig. 11–9 shows a round bar of mild steel, ruptured by incorrect forging technique. In this and similar cases, when reductions in size are undertaken, the correct procedure is to apply force to the metal in such a manner as to keep it largely in constant compression. The proper sequence in the reduction of a large round shaft is to (1) forge it to a square section of approximately the desired diameter; (2) rotate it through an angle of 45 degrees to shape it into an octagon; and (3) round it up with light pressure or blows. This sequence is shown in Fig. 11–10. An exception to this procedure is made when large ingots are first forged lightly to a round to consolidate their surfaces before heavy reductions are made. More effective than flat dies in reducing the size of large round shafts of steel or ingots are V-shaped dies which contact the metal on three points of its periphery. This method assists in locating the work and also causes deformation to take place at three places simultaneously with each stroke. Fig. 11–11 shows the sequence of the steps in the production of a weldless ring under a steam hammer.

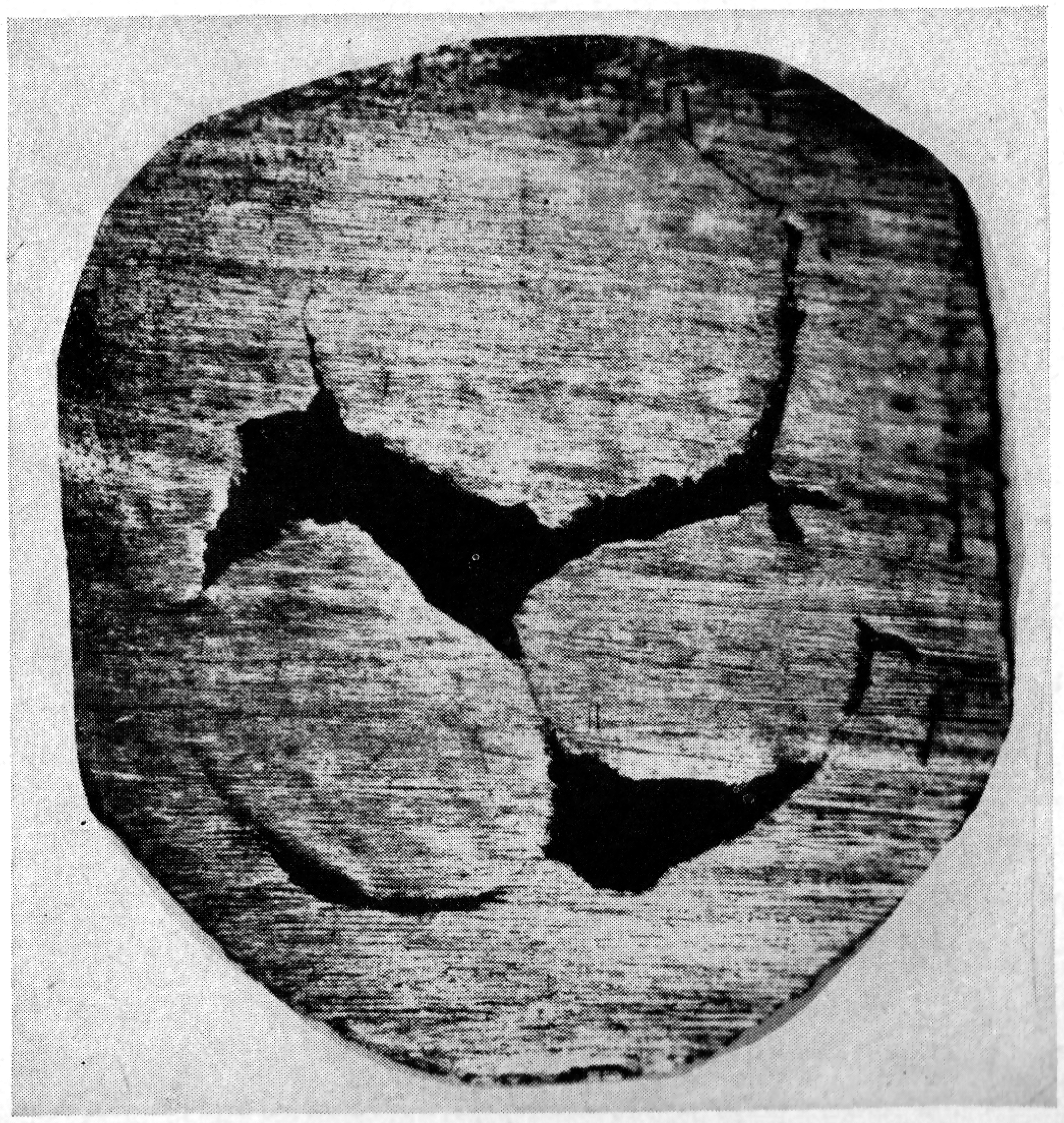


FIG. 11–9. Failure in a forged bar of mild steel, resulting from improper forging technique.

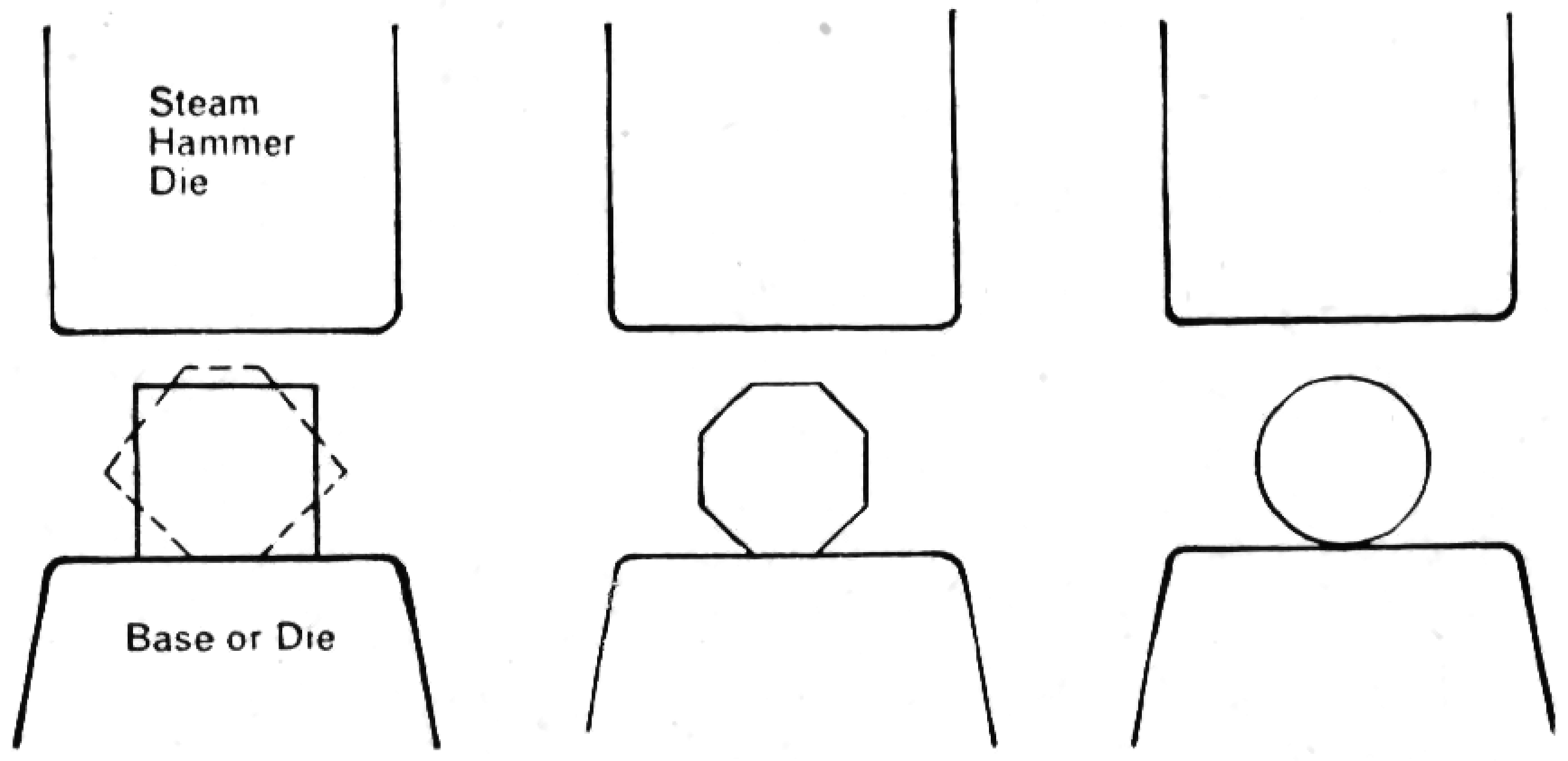


FIG. 11–10. Proper sequence in the production of round shafts by forging.

In whatever form it is applied, the mechanical energy expended on the plastic deformation of a metal should be adequate to insure its penetration into, and its effect on, the innermost part of the section. Unless adequate, the total force will be dissipated in causing the metal to flow on its surface only, which may result in a serious internal defect. The energy requirement is an increasing function of the size of the section. Other important factors are the plastic resistance of the metal and the permissible forging temperature.

11–10. Forging Processes and Equipment. Modern mechanical production equipment for the plastic working of metals includes helve hammers, steam or air hammers, board drop hammers, forging machines, forging presses, rolling mills, and extrusion presses.

One of the first mechanical forging devices consisted of a heavy wooden beam pivoted near one end and carrying an iron head on the other. Revolving cams, actuated by water power, intermittently raised the head and allowed it to fall on an anvil. No provision was made to maintain the surfaces of the hammer and anvil parallel except in one position.

11–11. Mechanical Power Hammers. The principle embodied in the beam hammer is utilized in the helve hammer, shown in Fig. 11–12, in which the beam or helve is cushioned with heavy rubber buffers which provide for positive and quick action when the hammer is in operation. The hammer is started when an idler pulley is brought into contact with a belt, which otherwise runs loosely on the pulleys. When the foot operating treadle is released, a brake is automatically applied, which stops the hammer. The striking rate varies from 250 to 400 blows per minute, with the energy increasing in direct proportion to the velocity.

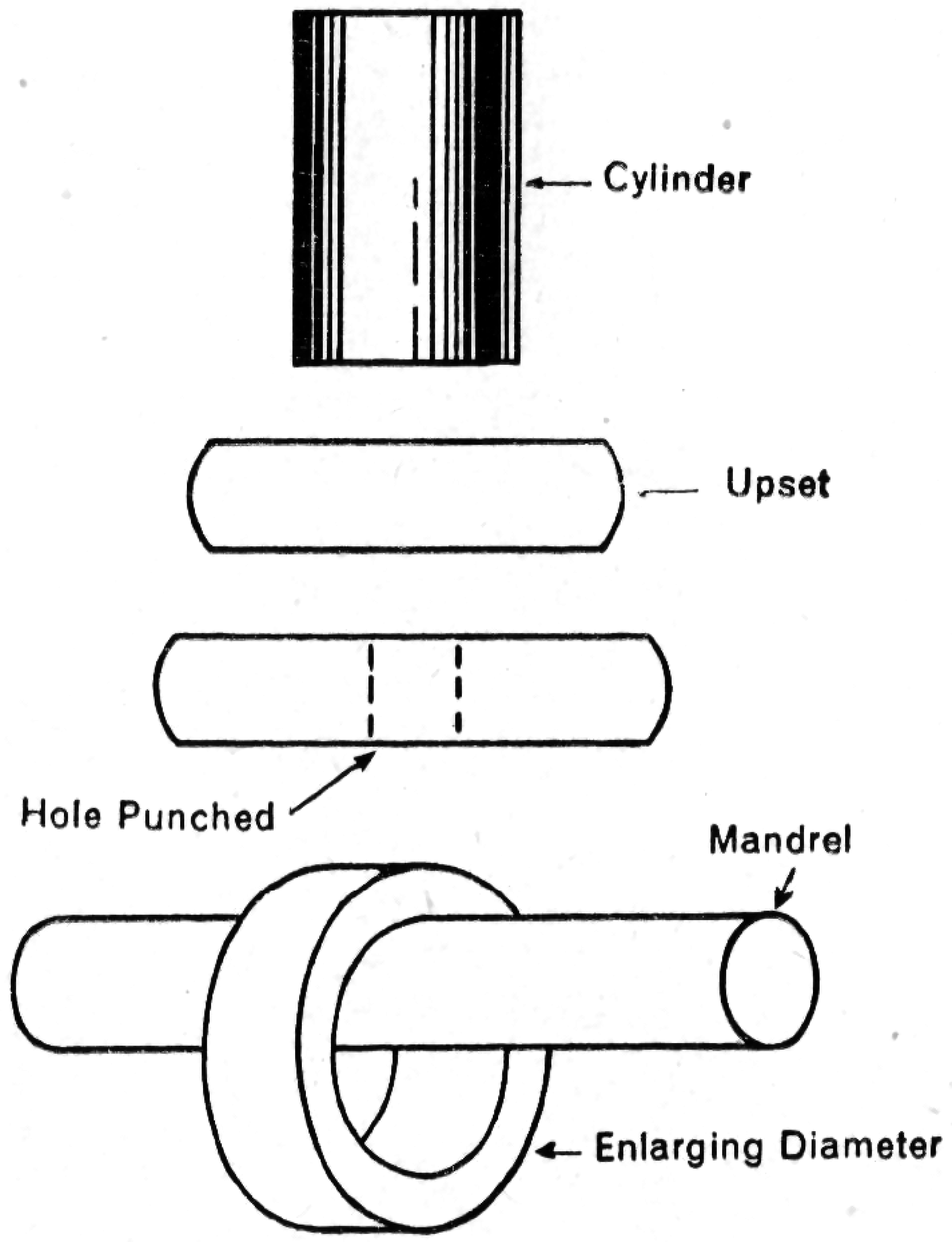


Fig. 11–11. Sequence of steps in production of weldless ring under a steam hammer.

The helve hammers operate efficiently on simple and relatively small forgings. Their size, or rating, which is the combined weights of the various parts constituting the hammer head, ranges from 15 to 500 lb.

A self-contained, air-actuated hammer operated by either a foot treadle or a hand lever is also used and is similar in construction to a small steam hammer. This unit is unique in that no external source of power is required, the air being supplied by a compressor built as an integral part of the construction. The maximum cross-section of metal which can be forged efficiently on these hammers is 7 sq in. of mild steel, and the maximum number of blows is 130 per min.

11–12. Steam Hammers. The first steam hammer was the invention of James Nasmyth, a Scotch engineer, and was built about 1848. Its development enabled forgings to be made which had been impossible before. In fact the hammer was capable of handling larger sections of steel than were then available. Three years later, an ingot made by Frederick Krupp of Germany was exhibited at an International Exhibition which, though weighing less than 5,000 lb, was the largest ingot made up to that time.

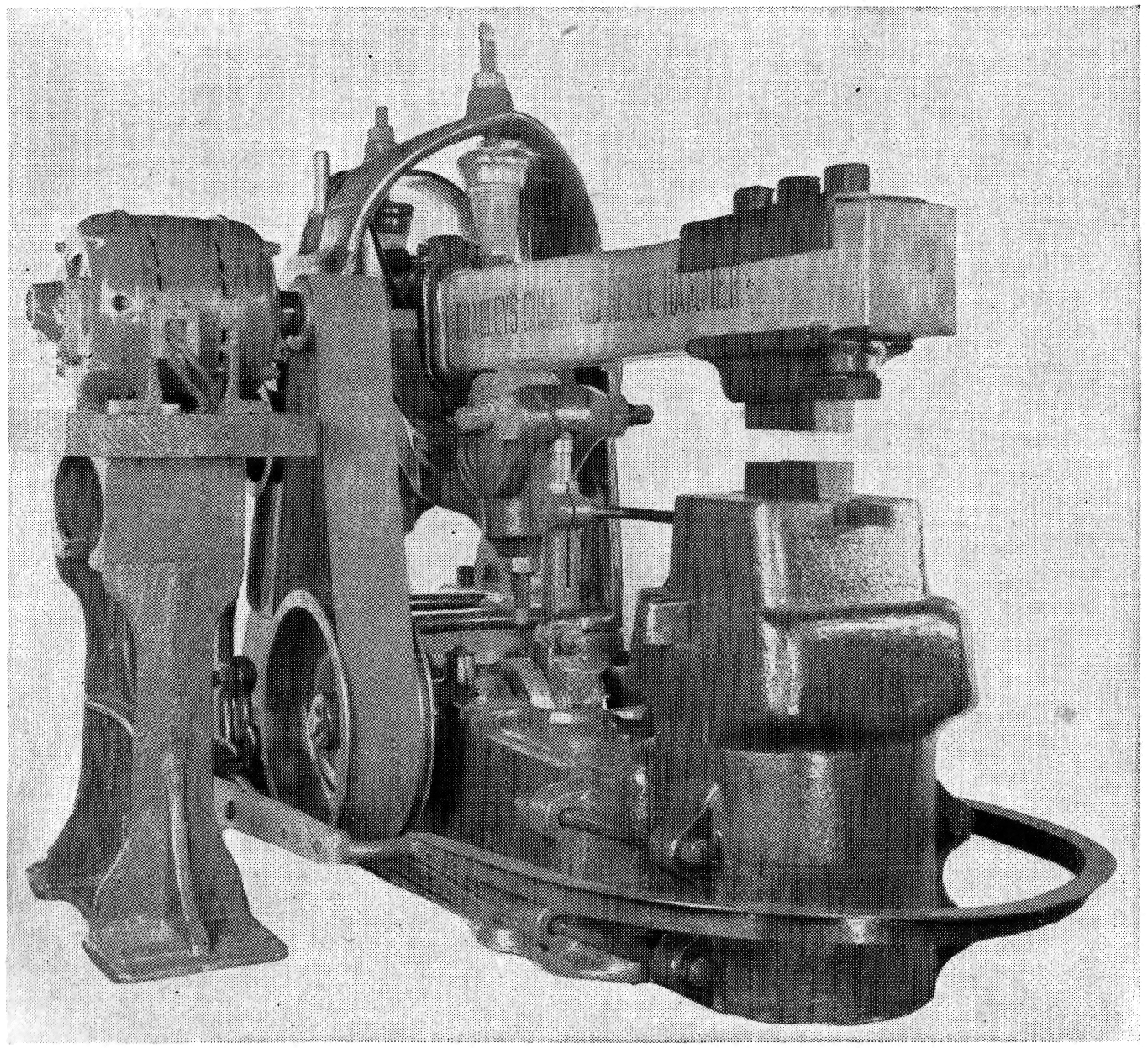


Fig. 11–12. A helve hammer. (Courtesy of C. C. Bradley & Sons, Syracuse, N. Y.)

The first steam hammer was a single acting device in which the steam was admitted into the cylinder below the piston to raise it to a height equal to the length of the cylinder, which determined the stroke. The whole reciprocating unit was then allowed to fall by gravity upon the work resting on the anvil or bottom die. Steam hammers utilizing this principle are now obsolete.

A modern steam hammer is patterned after the steam engine and is propelled by the admission of steam into the cylinder, both below and above the piston, greatly accelerating its velocity and increasing its efficiency and potential energy. It operates equally well on either compressed air or steam pressure ranging from 80 psi to 120 psi. Its rating or size is based on the nominal weight of all the reciprocating parts, which consist of the ram, piston, rings, and piston rod. Steam hammers range in size from 200 to 25,000 lb and are classified as single or double arch, the frame supporting the cylinder consisting of a half arch or a full arch respectively, as shown in Figs. 11–13 and 11–14. Both types of construction are widely used for general forge work with flat dies. As a study of the two designs suggests, the double frame hammers are for larger and more severe forging operations. The single arch hammers range in size from about 200 lb to 5,000 lb, while the double frame hammers range from 1,000 to 25,000 lb.

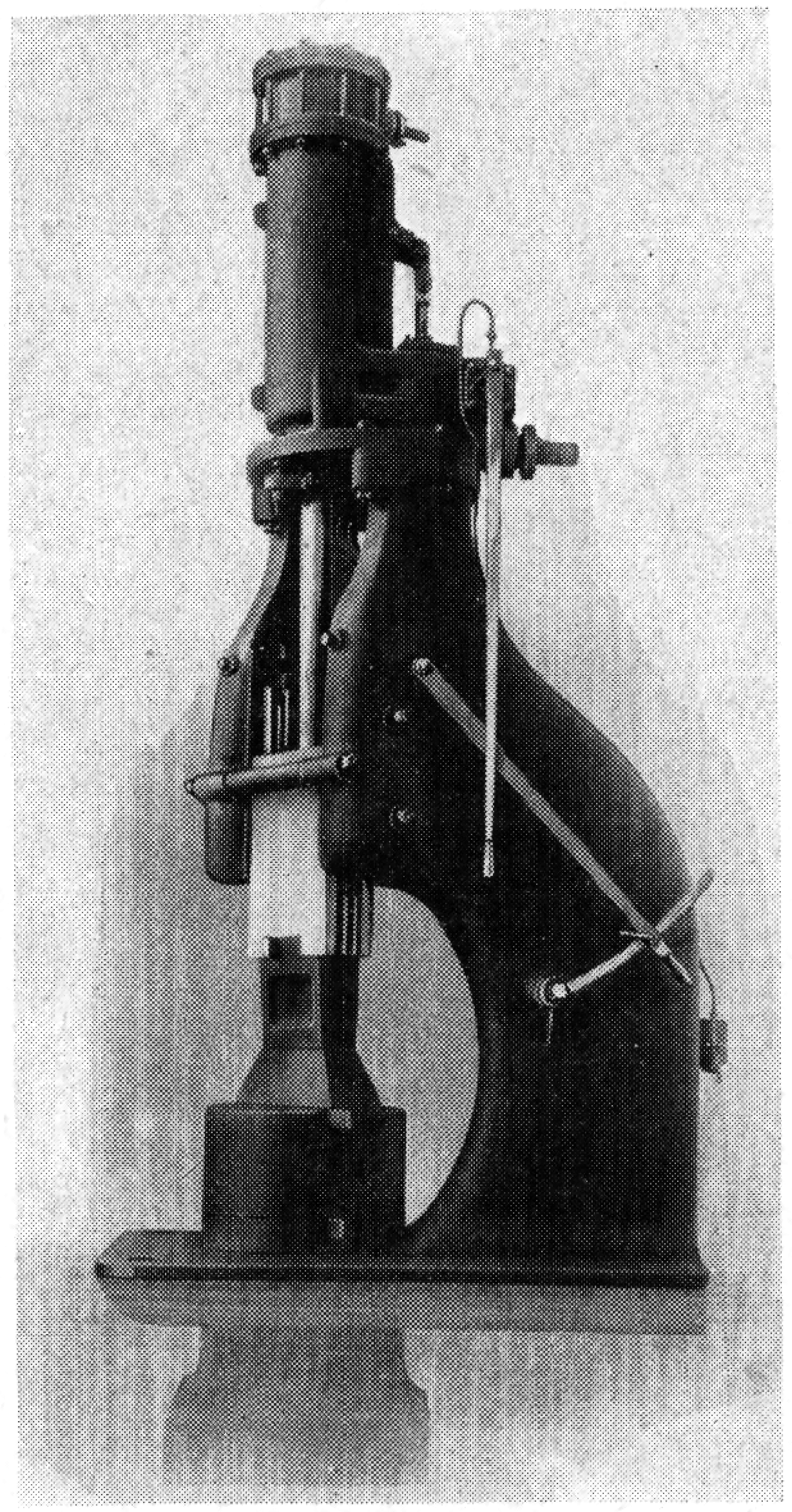


Fig. 11–13. A single arch steam hammer. (Courtesy of Chambersburg Engineering Co., Chambersburg, Pa.)

In the smaller sizes (less than 400 lb) the anvil block is cast integrally with the frame and is made of an alloy cast-iron or cast-steel, while for the larger hammers the anvil block is cast as a separate unit and rests on its own foundation. In order to obtain the maximum efficiency from the total available energy of the hammer, the ratio of the weight of the anvil block to that of the falling weight of the hammer parts varies between 15 and 25 to 1. This means that the anvil of a rated 20,000-lb hammer weighs 500,000 lb.

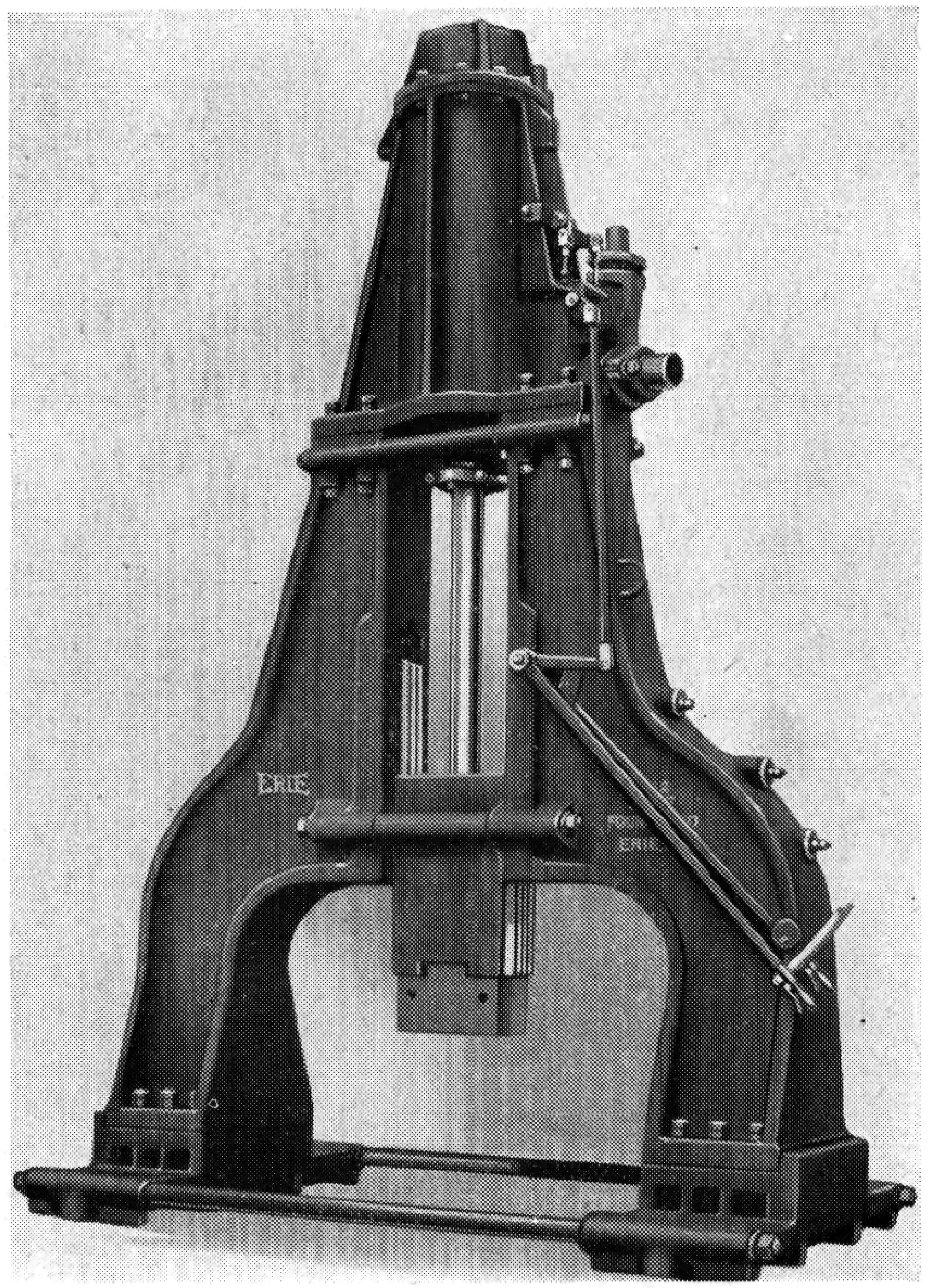


Fig. 11–14. A double arch steam hammer. (Courtesy of Erie Foundry Co., Erie, Pa.)

The side frames of steam hammers are attached to the base with heavy bolts, on which are mounted coil springs to absorb the shock on both the bolts and the frame when the hammer is in operation. Adjustable guides or ways, fastened to the frames with bolts, provide proper alignment of the upper with the lower dies, as may be necessary from time to time.

A steam hammer operated with a foot treadle or a hand lever will deliver blows of both variable intensities and velocities at will.

11–13. Hammer Forging. Pressure applied to hot metals by a steam hammer is exerted quickly and is of short duration. As a result, the grains nearest the surface and the point of stress are most affected by each blow. Therefore the progress of the refinement of the grain size takes place slowly and, unless the reduction of the section is sufficiently great or the section is a thin one, a general improvement throughout the section will not be obtained. For this reason large forgings are preferably produced by pressing or squeezing under a hydraulic press rather than by the high velocity impact of a steam hammer.

Since the potential energy of a steam hammer increases as the square of the velocity, it would appear that a light hammer falling through a long distance might have the same potential energy and, consequently, the same effect upon the metal as a heavier hammer falling through a shorter distance. That supposition, however, is erroneous, for a heavy hammer takes a longer time to come to rest and therefore effects deeper results. Furthermore, too great a velocity of impact may bring about the destruction of the metal, rather than its plastic flow, because of insufficient reaction time. The potential energy of a steam hammer to produce effective work is, therefore, a function of mass and of velocity.

11–14. Drop Hammers. Die forgings are produced with board drop and steam drop hammers, shown in Fig. 11–15 and Fig. 11–16, respectively.

Board lift, gravity drop hammers are actuated by iron rolls set at the top of the hammer on eccentric centers, which alternately raise and release the hammer head by engaging a hard wood board that is attached to the hammerhead or ram. The energy delivered by this type of hammer is a function of the weight of the head and the distance through which it travels; therefore, blows of variable intensity can be delivered only by resetting the actuating mechanism and varying the length of the stroke. Older hammer design provided for one roll on each side of the board, which limited the maximum weight of the moving parts commercially practicable to about 2,500 lb. Modern hammers, however, employ four rolls, two on each side; and, by thus distributing the stress on the board, it has been possible to increase the weight of the moving parts to a maximum of 7,500 lb. These hammers are driven by belt from a line shaft or directly by electric motors located on the hammer.

Steam drop hammers function mechanically like other steam-operated hammers; they differ only in their construction, which permits adjustments of guides to obtain a close alignment of the lower and upper dies, As with the steam hammer, blows of variable intensity can be delivered since the steam is used both to lift the ram and to force it down. The potential energy of a steam drop hammer is about twice that of a board hammer of equal rating.

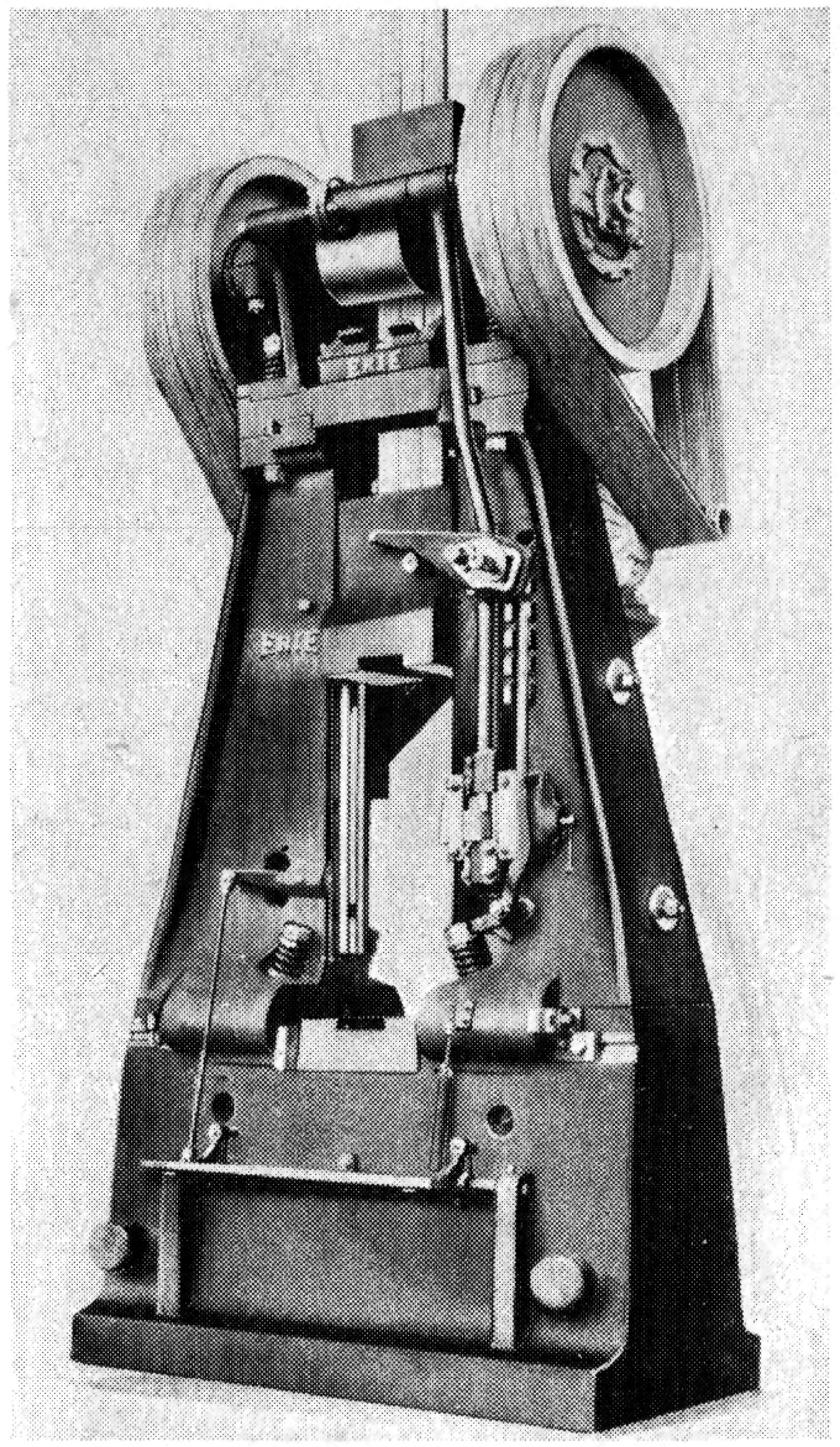


Fig. 11–15. A board drop hammer. (Courtesy of Erie Foundry Co., Erie, Pa.)

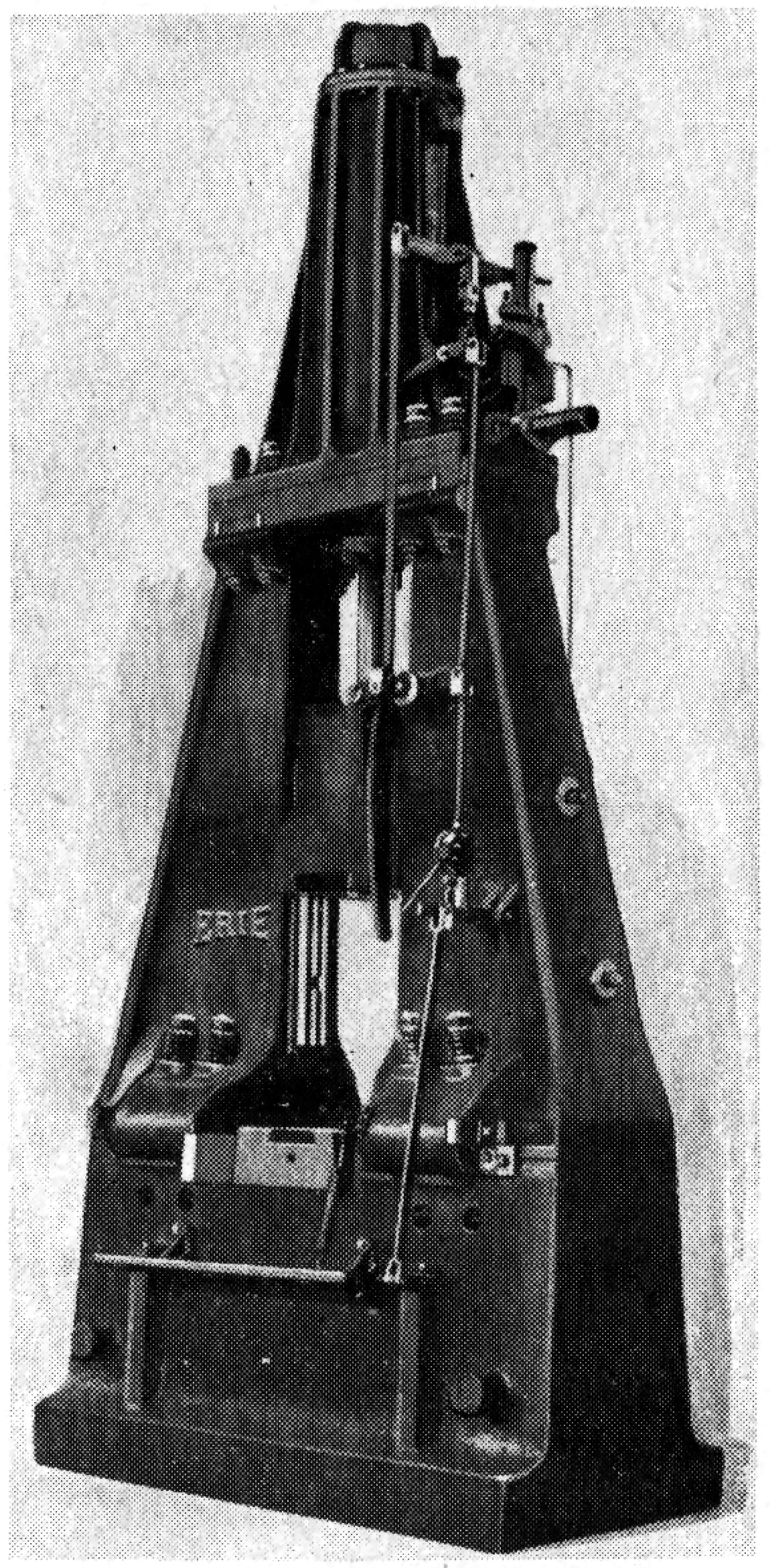


Fig. 11–16. A steam or air drop-forging hammer. (Courtesy of Erie Foundry Co., Erie, Pa.)

Steam drop hammers range in size from about 1,000 to 50,000 lb falling weight. The ratio of the weight of the anvil to the moving parts of both hammers is similar to that of the steam hammer.

Both the board drop and the steam (or air) drop hammers are used for the production of forgings of a wide diversity of size, weight, and degree of difficulty.

11-15. Forging Presses. Certain inherent advantages in the production of large forgings—such as die blocks, heavy guns, shafts for power transmission, and armor plate—favor the hydraulic press in preference to a steam hammer.

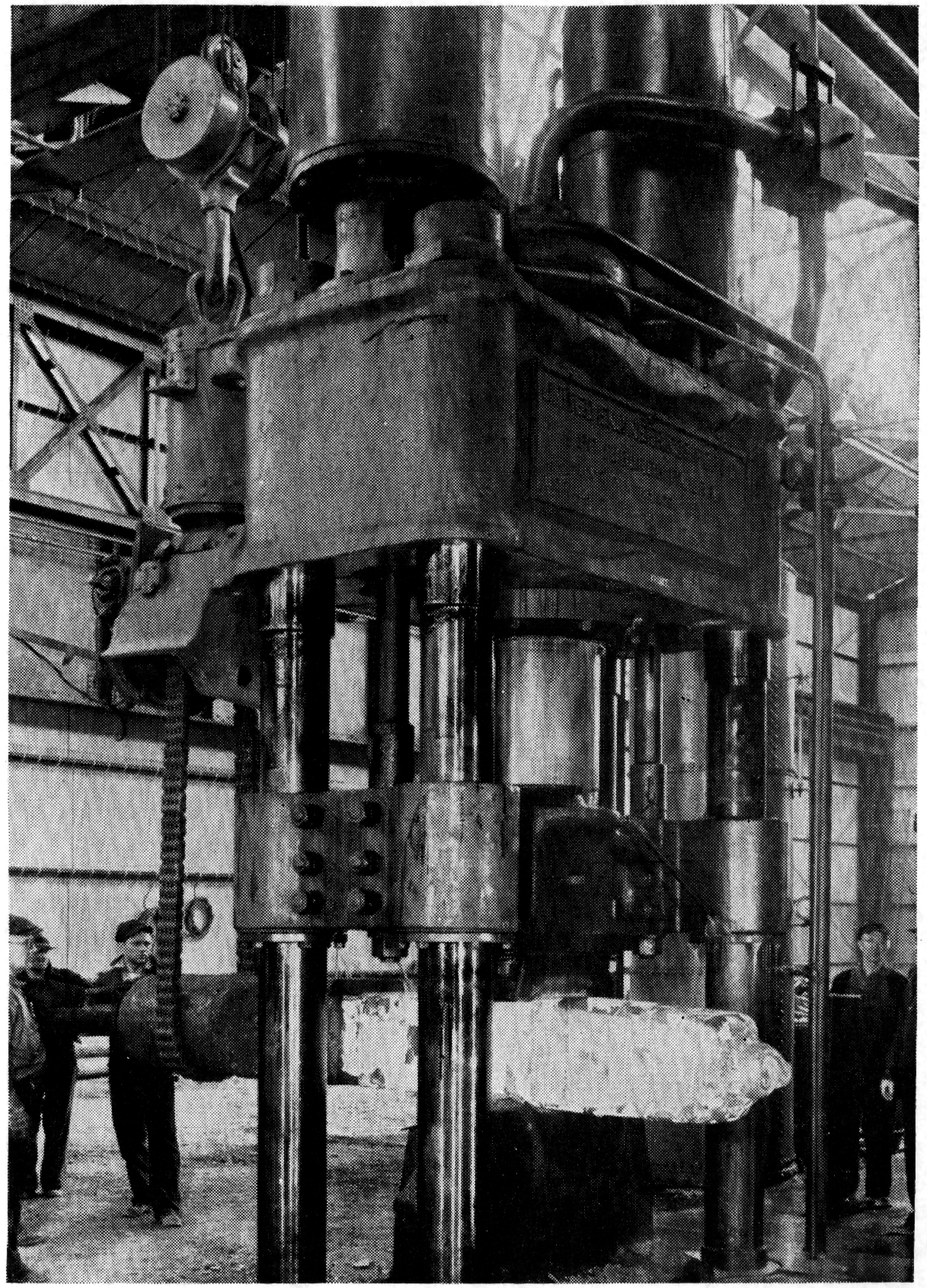


FIG. 11–17. A 1,000-ton forging press. (Courtesy of United Engineering Co., Pittsburgh, Pa.)

Modern high-speed hydraulic forging presses, such as the one shown in Fig. 11–17, are operated by air hydraulic, steam hydraulic, or straight hydraulic systems and have a capacity from 150 to 15,000 tons. These presses are capable of producing work far beyond the capacity of any steam hammer, and the *cogging down* or reduction by the squeeze action

of the press improves the somewhat loose texture of the core of large ingots more effectively than impact pressure of the steam hammer could.

It is generally recognized that the advantages of both higher production and economy of operation favor the use of the steam hammer in sizes below 3,000 lb for equivalent types of work; but, in the range of sizes above this, the hydraulic press is more acceptable.

Steam hammers and hydraulic presses are commonly compared as to the approximate required size for forging ingots, as shown in Table 11–2.

TABLE 11–2

GENERAL COMPARISON OF RELATIVE SIZE OF STEAM HAMMERS AND HYDRAULIC PRESSES

Rated Size of Hyd. Forging Press (Tons)	Approx. Max. Ingot Size (In.)	Rated Size of Steam Hammer (Lb)
300	12	3,000
500	16	5,000
750	24	10,000
1,000	30	16,000
1,500	40	25,000
2,000	48	50,000
3,000	60	
4,000	64	
5,000	70	

Hydraulic forging presses receive their pressure through the medium of some fluid, such as oil or water. Pressure is imparted to the fluid by means of pistons which are actuated by steam, compressed air, or water. Where water is used, the pressure is obtained through motor driven pumps. The hydraulic pressure is delivered to a cylinder from a pump or accumulator, from a steam hydraulic intensifier, or from an air hydraulic intensifier, which increases the low working pressure of 90 to 200 psi to a hydraulic pressure of about 6,000 psi.

Some of the distinct advantages attributed to the hydraulic forging press are (1) that the pressure is applied to the metal slowly, in contrast to the high velocity impact of the steam hammer, and thus effects deeper results; (2) that the pressure is allowed to remain active for a short time after the metal has yielded to the stress, which simulates a *kneading* action not obtainable on large sections with the steam hammer; (3) that the full capacity pressure can be applied regardless of the travel of the head, whereas the potential energy of the steam hammer varies directly as the travel of the ram; and (4) that the hydraulic press works silently with an absence of excessive vibrations and ground tremors.

While not well adapted for forming thin sections such as are found on some drop-forgings, the presses are admirably adapted for upsetting, punching, and drawing out large shafts directly from the ingot.

As an instance of the production obtainable with a modern quick acting press, it is reported that a 2,000-ton hydraulic press, starting with a 45-in. diam ingot, cogged down and finished a shaft 15 in. in diam and 30 ft long in one heat. Ingots weighing well over 500,000 lb, shown in Fig. 7–10, are successfully forged on hydraulic presses.

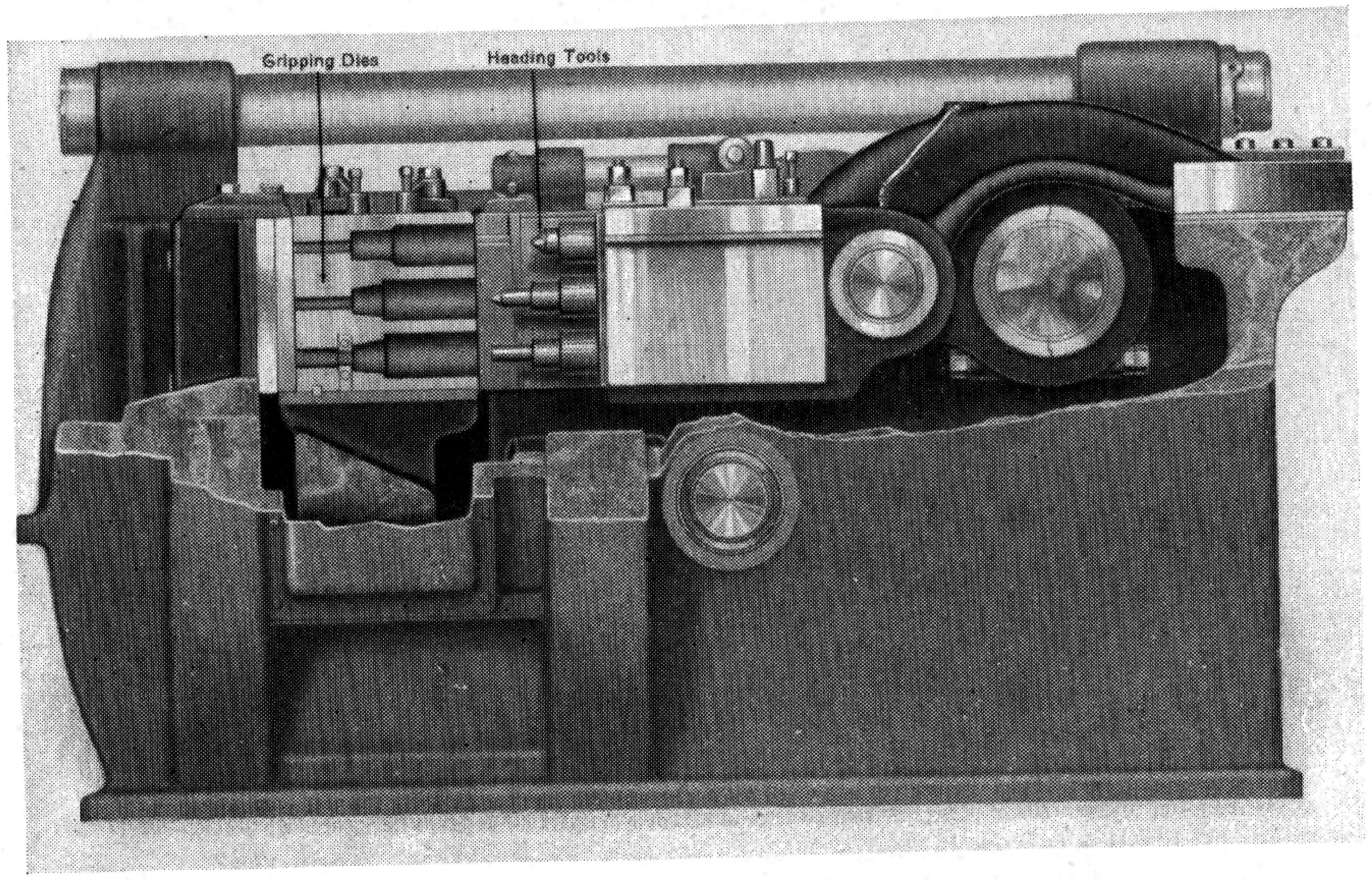


Fig. 11–18. A forging machine in which the production mechanism is shown. (Courtesy of National Machinery Co., Tiffin, Ohio.)

11–16. Forging Machines. For production capacity, and a wide variation in shape and weight of its products, the forging machine shown in Fig. 11–18 is an indispensable forging tool. Predominantly its use consists in the production of forgings which require upsetting or piercing of the metal with the aid of dies conforming to the desired shape of the product. The machine operates in a horizontal plane, and its production mechanism is centered about a *heading* tool and two dies called *gripping* dies. When the machine is put in motion by the depressing of a foot treadle, one of the grip dies slides laterally toward the other, which is stationary; the hot metal has been placed between these two, with a length equal to that required for the forging extending beyond the inner surface of the die. While the two gripping dies hold the metal securely, the heading tool moves axially against the extended and heated end of the bar and upsets or forces the metal back into recesses or grooves in the grip dies or in the heading tool or partly in both the grip dies and heading tool. Forgings such as those shown by Fig. 11–19 are the result of multiple operations performed in different recesses and carried out in sequence in quite rapid succession, requiring the heating of the metal but once. Simple forgings such as bolts and rivets are produced in one operation.

The metal, which extends beyond the die face upon which work is done, is called *unsupported* stock, because it is not restrained from bending or buckling when it is engaged by the heading tool. To avoid excessive bending and to enable concentric upsets to be made, as shown in Fig. 11–20, the first and basic rule governing successful machine upset forging limits the maximum length of the metal to three times its diameter when the upsetting is done with flat faced or unrecessed heading tool. If the metal is restrained, except in a plane parallel with its axis, by being contained within a counterbored heading tool or the grip die, lengths in excess of three diameters may be upset successfully. To effect this restraint, the maximum diameter of the recess or counterbore should not be more than one and one-half times the diameter or thickness of the metal. The various steps employed in the production of parts requiring lengths more than three times the diameter of the metal are shown in Fig. 11–21.

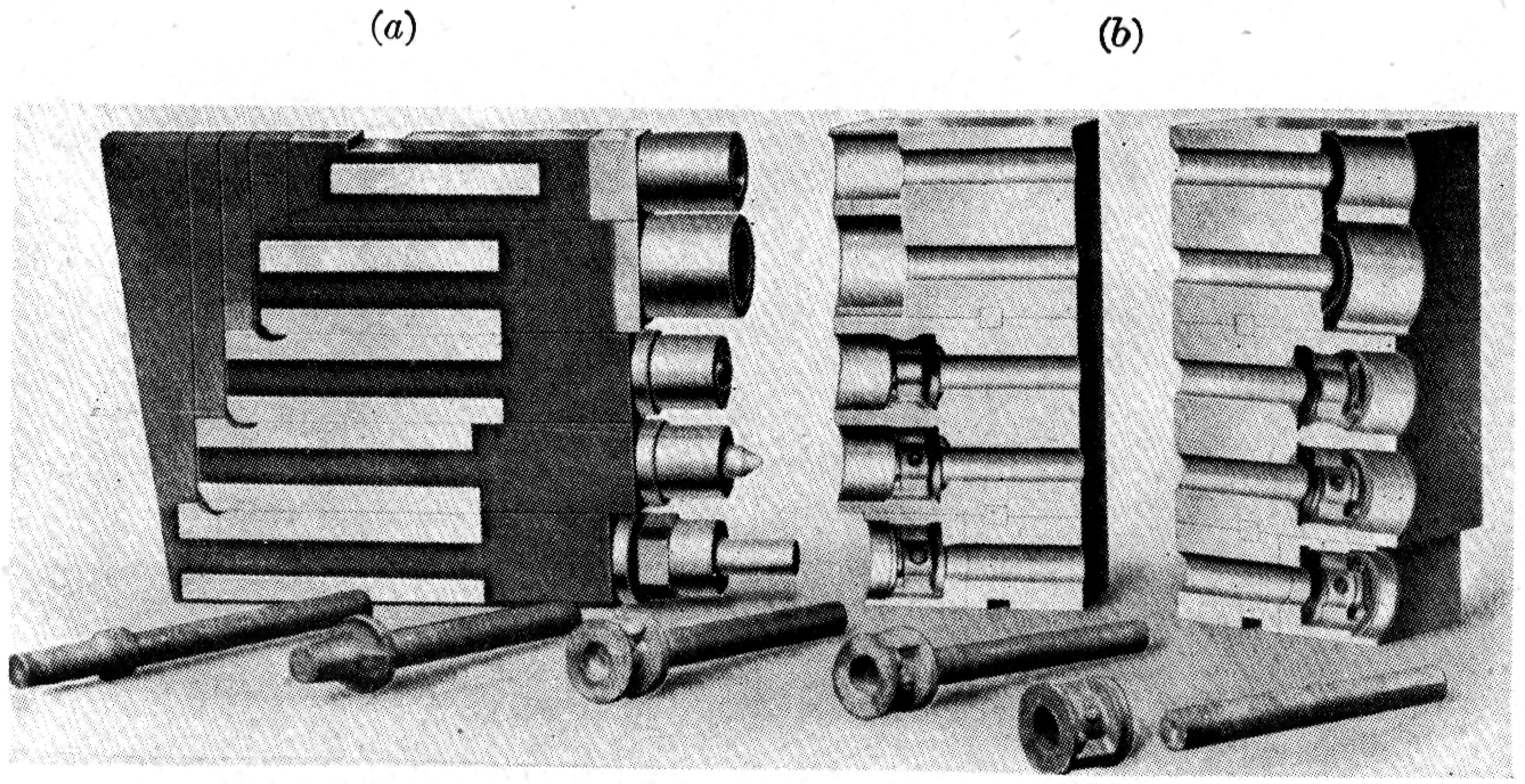


Fig. 11–19. At (*a*), a set of heading tools and at (*b*), gripping dies. Sequence of operations performed and the final product are shown in the foreground.

In order that sufficient friction be developed to prevent slippage of the metal without applying undue side pressure through the gripping dies during the upsetting operation, it is advisable that the minimum length of the grip dies be not less than 3 in. in addition to the diameter or thickness of the metal.

Forging machines range in capacity from 1 in. diam stock to 9 in.

In increasingly larger amounts bolt heads are formed of semicold-rolled steel bars in sizes up to 1 in. on cold heading machines, shown in Fig. 11–22, which operate on the same basic principle as the forging machine described above. A coil of wire located on a revolving drum behind the machine is automatically led in, cut, headed, and ejected at an astonishingly high rate of production.

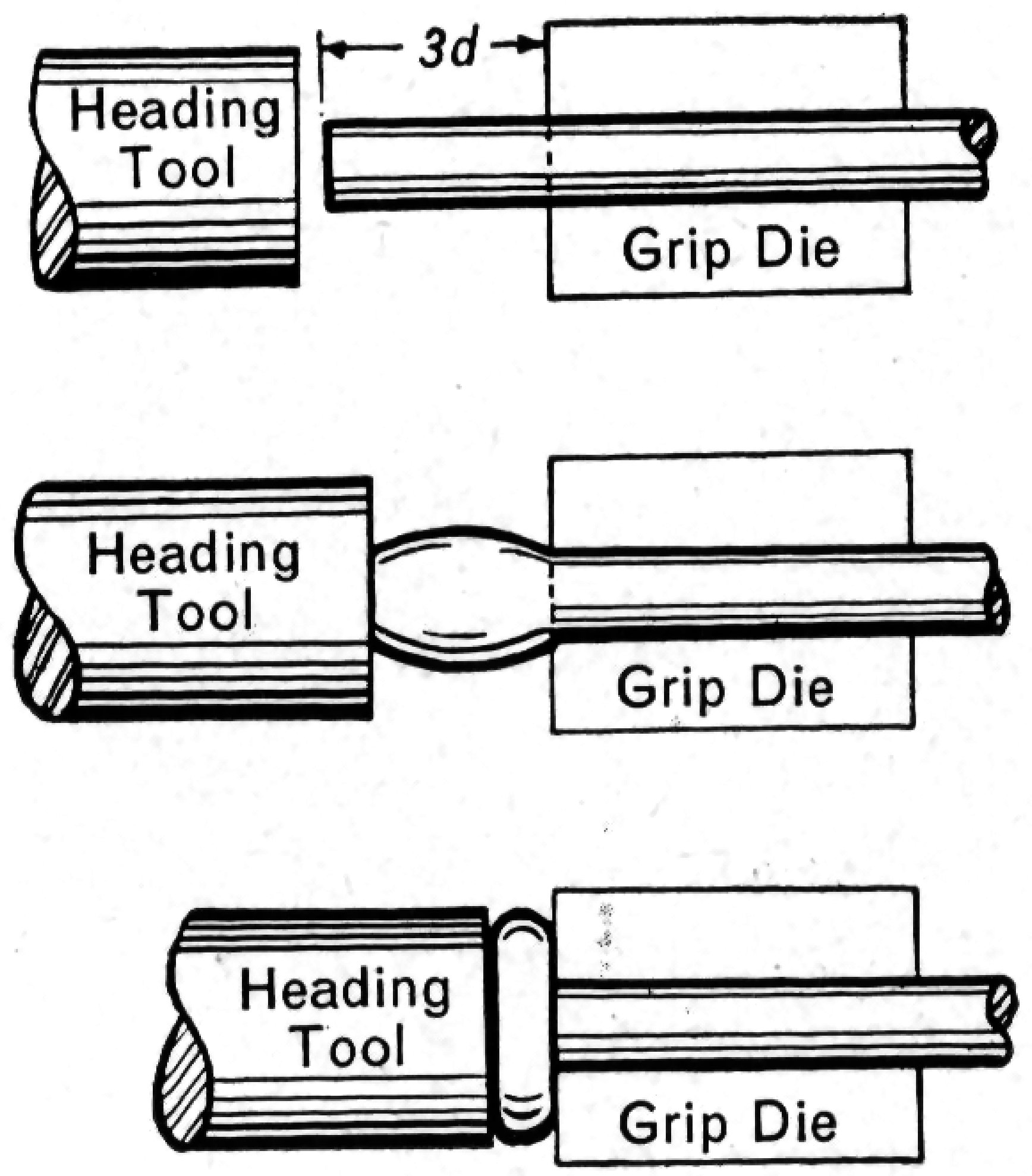


Fig. 11–20. Limit of length of unsupported stock that can be gathered or upset in one blow without injurious buckling is not more than three times diameter of bar.

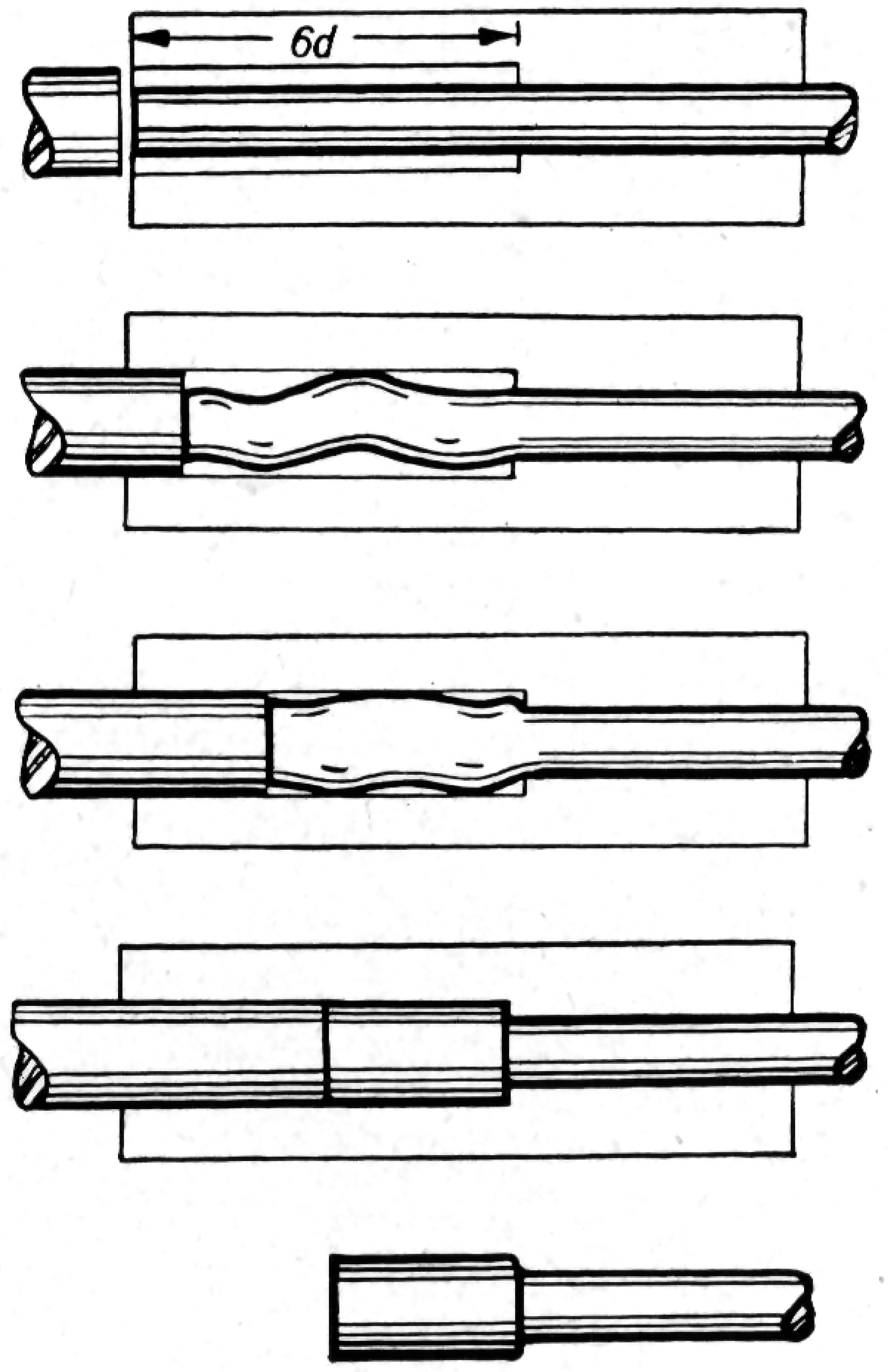


Fig. 11–21. Lengths of stock more than three times diameter of bar can be successfully upset in one blow, if diameter of upset made is not more than one and one-half times bar diameter.

11–17. Type and Varieties of Forgings. All forgings may be classified into two groups—smith forgings and die or drop-forgings. The former are those whose shape has been attained by working under a press or hammer with flat or V dies and employing an assortment of tongs, or suitable mechanical manipulators for handling the hot metal, with other tools which, except for their size, are similar to those of the early smith. These forgings are usually forged in one plane and are used for large power transmission shafts, disks for turbines, locomotive driving rods, and large crankshafts for marine engines.

Die or drop-forgings are those produced between two dies, in which impressions conforming to the finished product are *sunk* or machined so that the forgings conform one to another in shape and dimensions. One of the dies is attached to the *ram,* while the other or lower one is securely keyed to the anvil or *sow* block of the hammer. In some respects drop-forging dies are analogous to the drag and cope halves of a foundry mold. However, drop-forgings are the result of working the metal in its hot plastic state. Drop-forging dies for the production of a pliers and an open-end wrench, used in the author's laboratory courses, are shown in Fig. 11–23. The principal parts of a die are shown in Fig. 11–24. Fig. 11–25 shows a typical drop-forging die for producing the part shown. Sequence of operations in the production of a connecting rod is shown in Fig. 11–26.

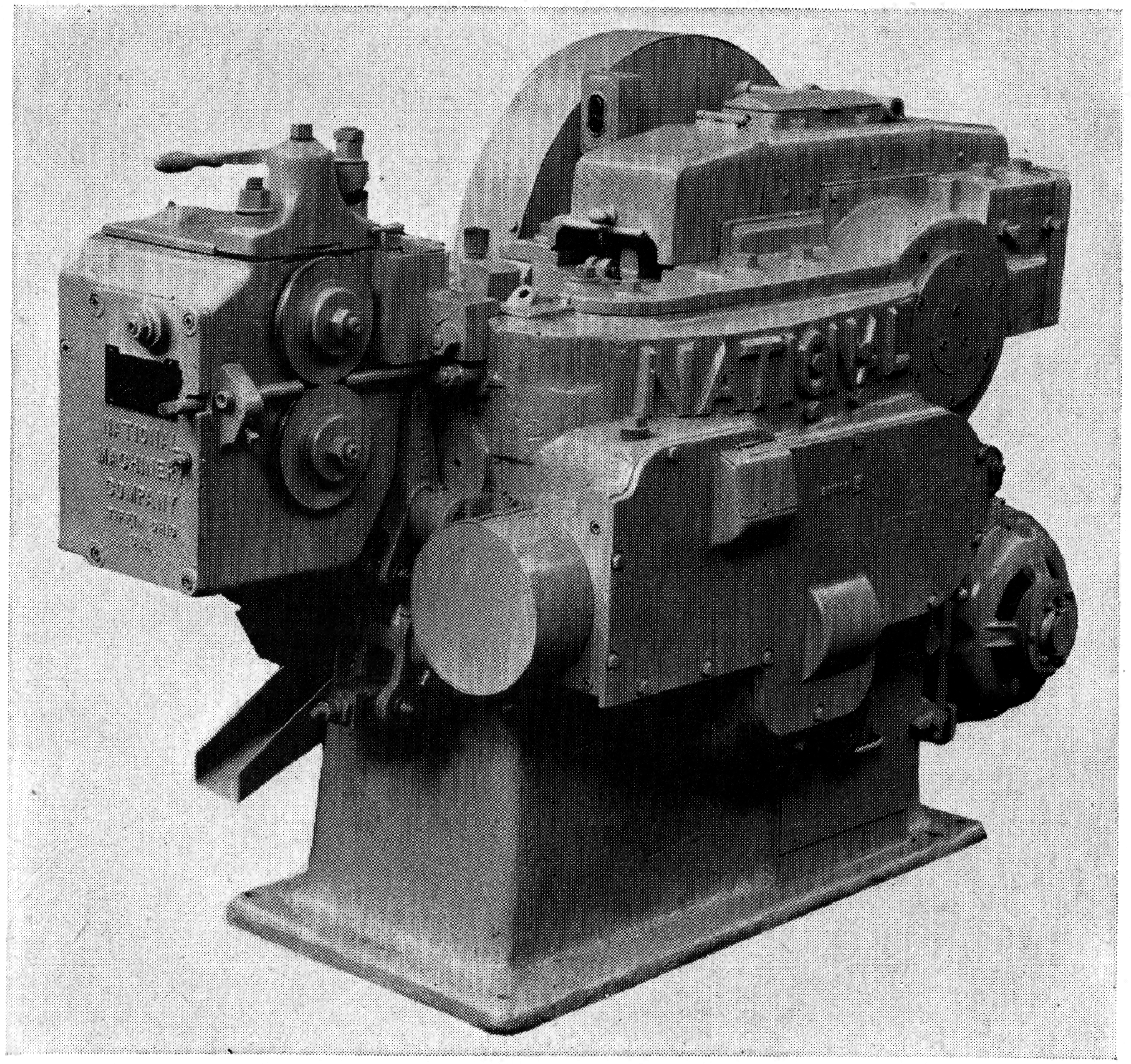


Fig. 11–22. A cold heading forging machine. (Courtesy of National Machinery Co., Tiffin, Ohio.)

A provision known as *draft* is necessary in all die impressions to facilitate the quick removal of the hot metal from the die to avoid loss of heat and reduced production through sticking, and to provide for a more ready

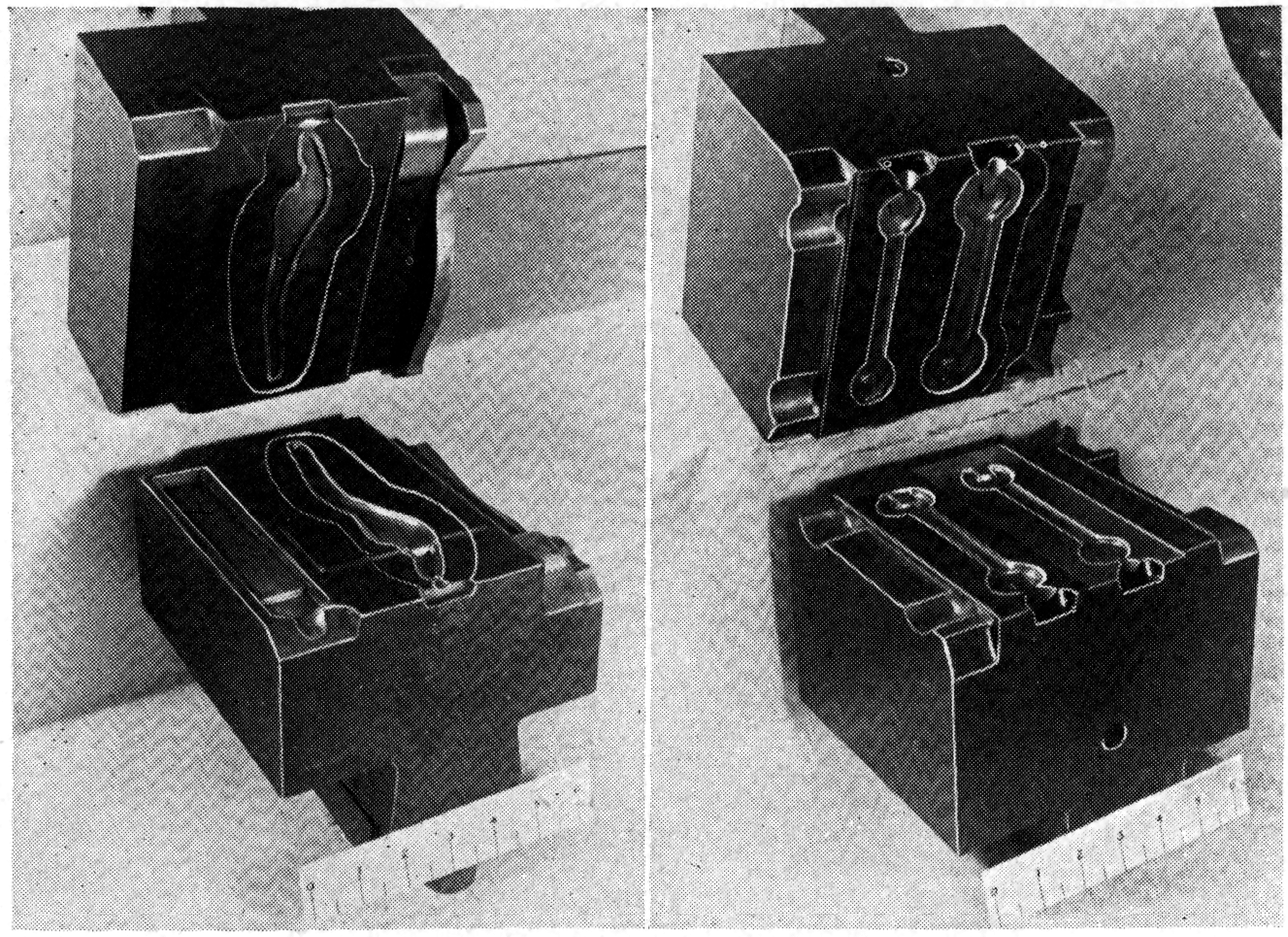


FIG. 11–23. At left, a drop-forging die for producing 6-in. pliers; at right, a drop-forging die for producing double-end wrenches.

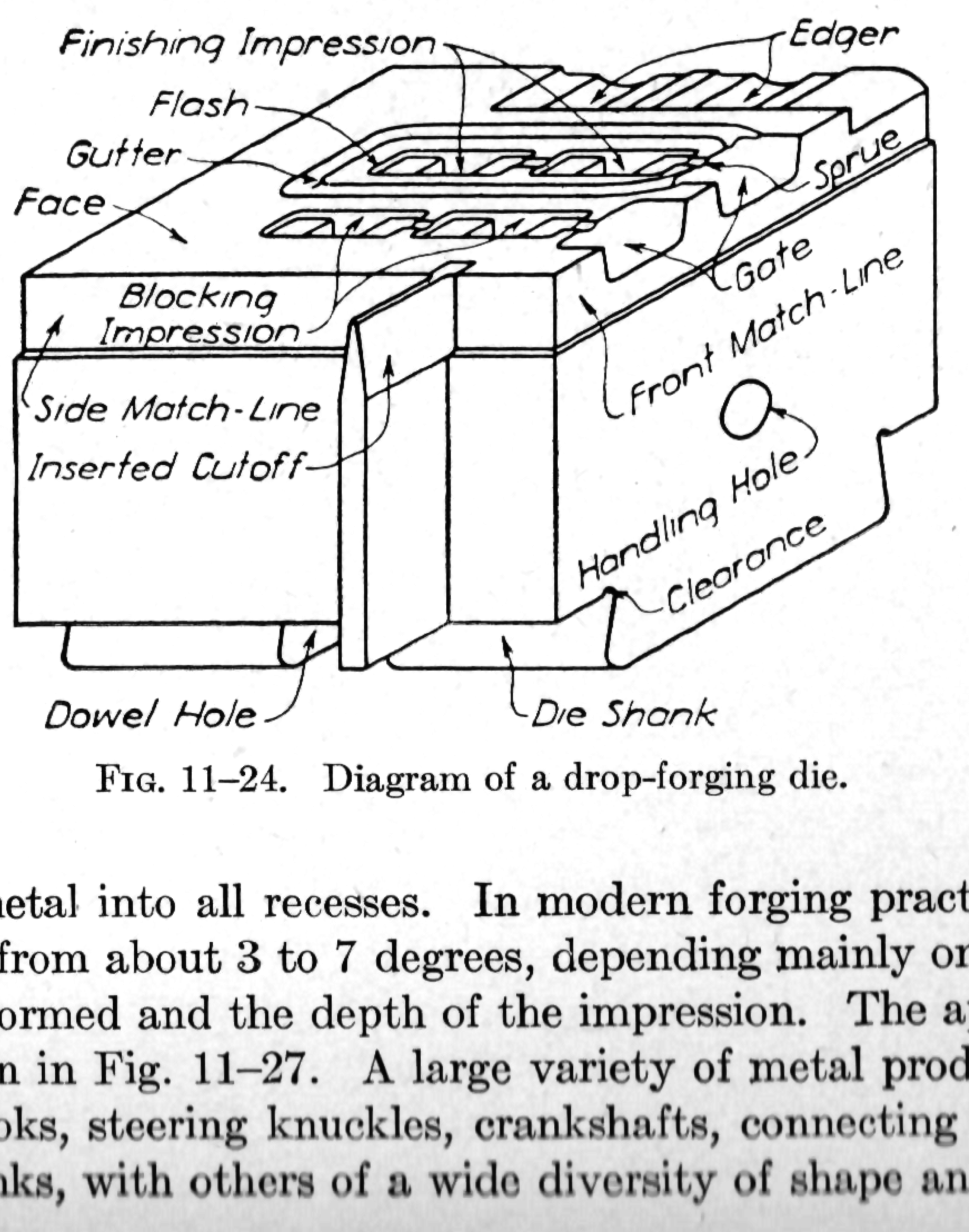

Finishing Impression
Edger
Flash
Gutter
Face
Sprue
Gate
Blocking Impression
Front Match-Line
Side Match-Line
Inserted Cutoff
Handling Hole
Clearance
Dowel Hole
Die Shank

FIG. 11–24. Diagram of a drop-forging die.

flow of the metal into all recesses. In modern forging practice this provision varies from about 3 to 7 degrees, depending mainly on the kind of metal being formed and the depth of the impression. The application of draft is shown in Fig. 11–27. A large variety of metal products such as wrenches, hooks, steering knuckles, crankshafts, connecting rods, levers, and gear blanks, with others of a wide diversity of shape and ranging in

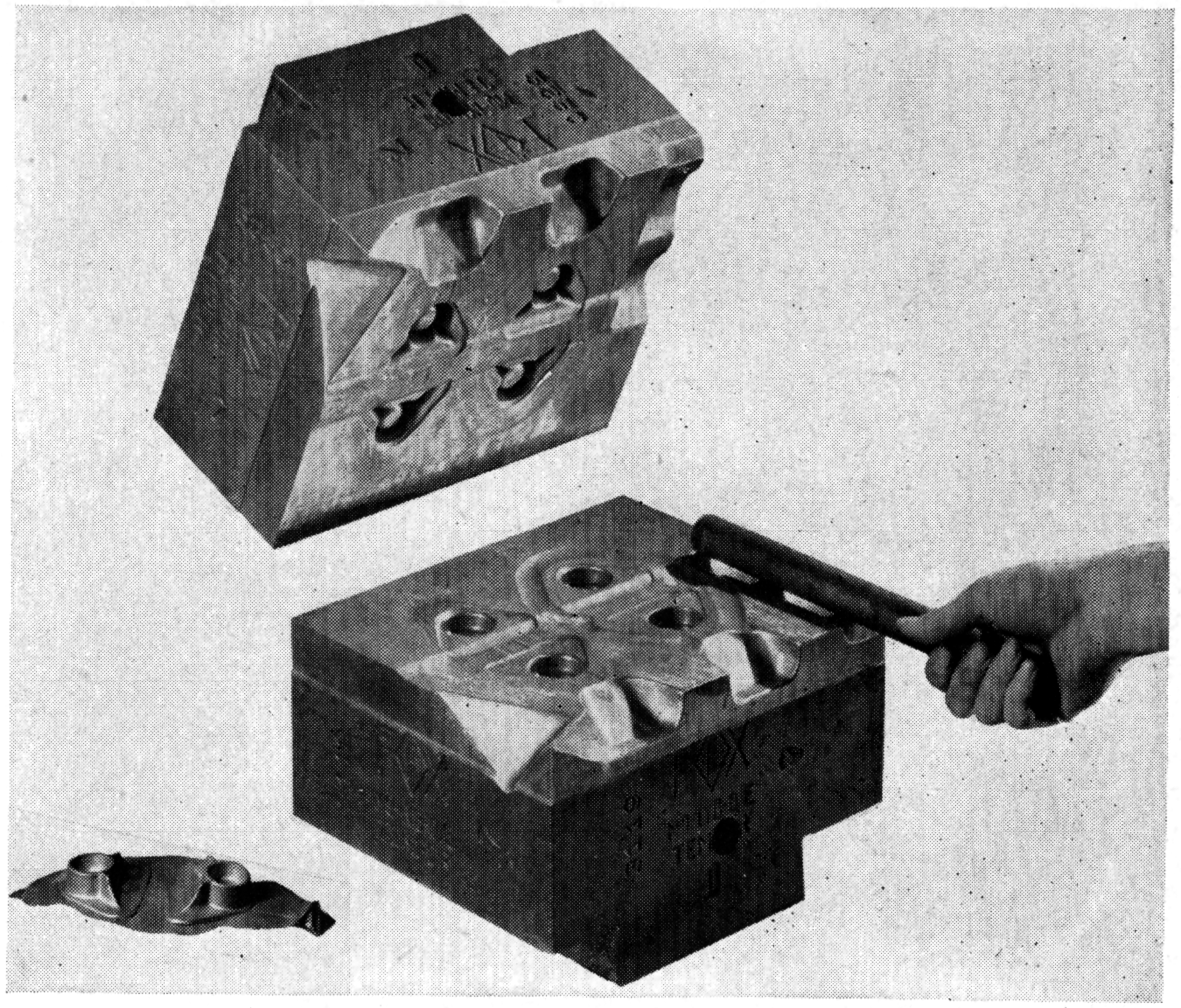


FIG. 11–25. Drop-forging dies for production of part shown at lower left.

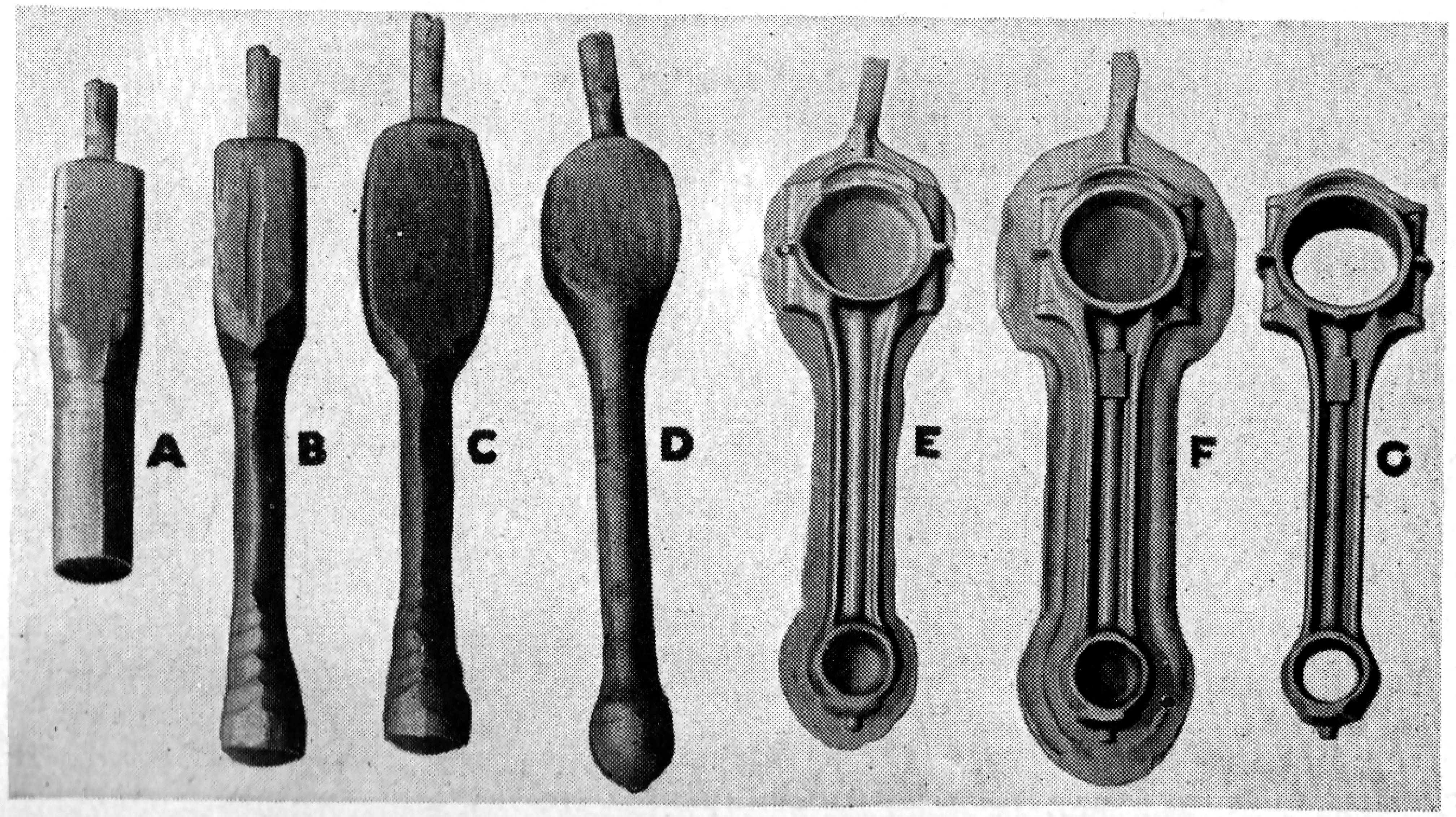


FIG. 11–26. Sequence of operations in production of forged connecting rod 38 in. long from billet 4$\frac{13}{16}$ × 4$\frac{13}{16}$ × 18$\frac{1}{2}$ in. Illustrations A, B, C, D, and E cover all operations performed in preforming and blocking impressions, while F and G show result of subsequent operations in finishing and trimming dies. (Courtesy of Drop-Forging Association, Cleveland, Ohio.)

weight from a few ounces to several hundred pounds, are made by the drop-forging method.

Die blocks must withstand severe impact stresses due to constant hammering, must resist abrasive wear, and must show a minimum amount of cracking and checking. Consequently, if they are to have a long productive life without any appreciable dimensional changes in the impressions, the steel selected must be a high quality electric furnace or open-hearth product of the correct analysis. The steel must also be carefully and sufficiently worked to yield the best structure, and heat-treated. The selection of a suitable grade or hardness of a die block may be governed by the following factors: (a) the nature of the forging such as shape, size, and weight; (b) the type of metal specified for the forging; (c) the quantity of forgings required; and (d) the type of forging equipment to be used. The composition and heat treatment of dies of various analyses are given in Tables 11–3 and 11–4. Depending on the complexity of the forging, the dies contain several provisions for shaping the metal prior to placing it in the finishing impression. Thus a connecting rod will be *fullered*, *edged*, and *blocked* in different parts of the die, shown in Fig. 11–24, and finally finished.

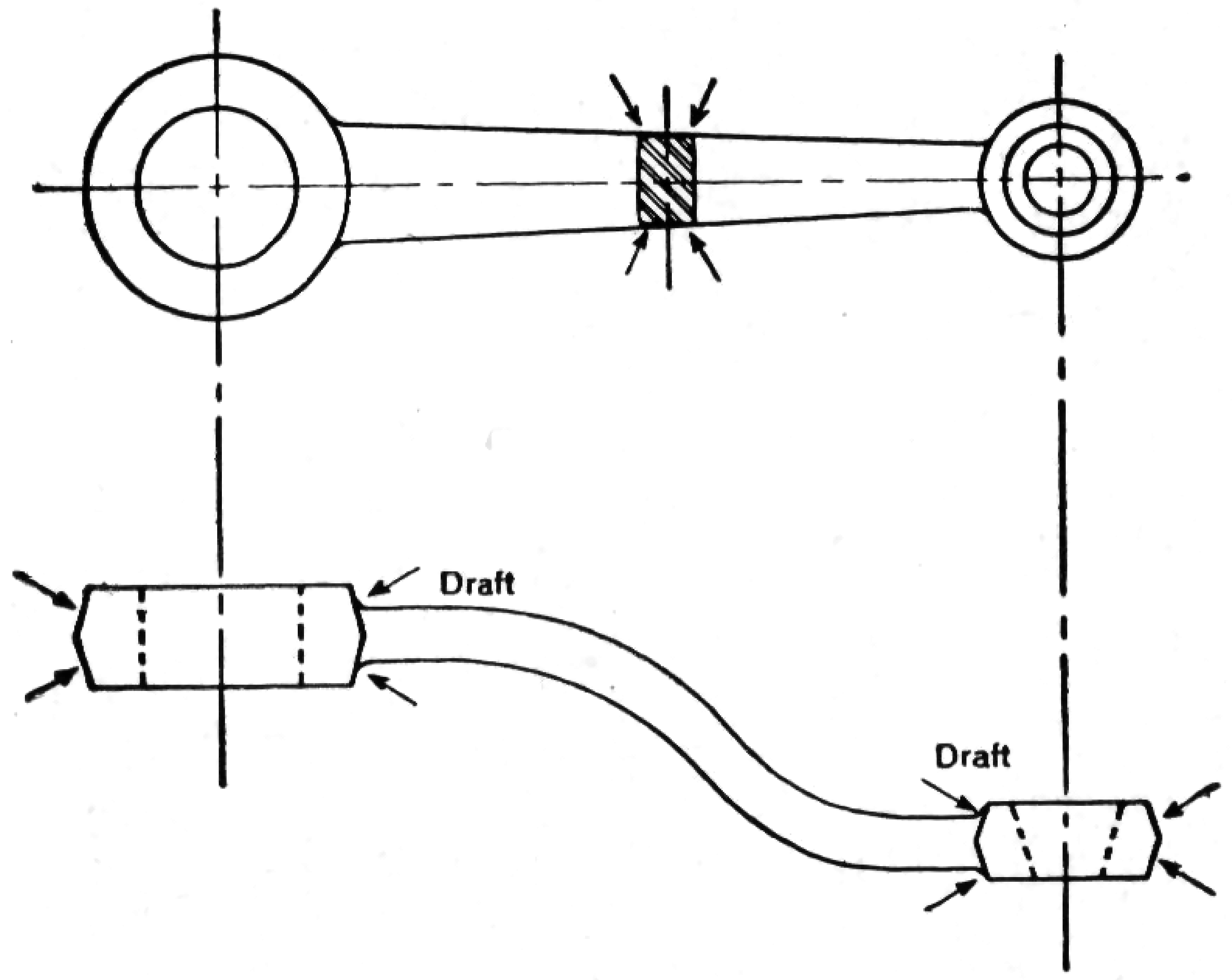


FIG. 11–27. Sketch showing draft provisions in a drop-forging.

11–18. Press Drop-Forging. In a comparatively recent practice many ferrous and nonferrous drop-forgings are produced by squeezing the metal in dies attached to a high-speed mechanical press.

While originally designed for hot or cold coining of drop-forgings produced by hammers to obtain closer dimensions, modern presses, because of accelerated operating speeds, are now employed to produce forgings directly from blanks. On parts adapted for press forging the

output of the press is from three to four times that of hammers. This higher production rate is attributable to the fact that the part is struck only one blow in each die impression and that knockout pins, provided in both top and bottom die, facilitate quick removal of the part. Other advantages of the press as compared to the hammers are that forgings of closer dimensions are obtainable, bosses and lugs are more easily filled, less draft is required, better metal flow into die cavities reduces flash, and less skill in operation is required. Fig. 11–28 shows a modern high-speed press.

TABLE 11–3

APPROXIMATE CHEMICAL COMPOSITION OF DIE BLOCKS

Steel No.	Purpose	Carbon	Manganese	Chromium	Van.	Molyb.	Nickel
1........	Hot-forging	0.60	0.70	....	....	....	....
2........	Hot-forging	0.70	....	....	0.25	....	....
3........	Cold-forging	0.85	....	....	....	....	....
4........	Drop hammer	0.60	0.70	1.00	....	....	1.50
5........	Drop hammer	0.60	0.70	0.90	....	0.20	....
6........	Drop hammer	0.60	0.80	0.75	....	0.25	1.50
7........	Drop hammer	0.60	0.70	1.15	0.15	0.50	....
8........	Drop hammer	0.60	0.60	0.90	....	0.70	1.75

TABLE 11–4

HEAT TREATMENTS FOR DIE BLOCKS*

Steel No.	Hardening Temp. (F)	Quenching Medium	Tempering Temp. (F)	Scleroscope Hardness	Brinell Hardness
1...........	1425–1475	Water	500–1000	50–70	352–512
2...........	1475–1525	Water	500–1000	50–70	352–512
3...........	1425–1500	Water	350– 600	70–80	512–600
4...........	1475–1550	Oil	600–1000	50–73	352–534
5...........	1475–1550	Oil	600–1000	50–73	352–534
6...........	1475–1550	Oil	600–1000	50–73	352–534
7...........	1500–1575	Oil	600–1000	50–73	352–534
8...........	1575–1650	Air	....	50–73	352–534

*ASM *Handbook* (1939 ed.).

In tonnage capacity these presses are, like hammers, suitable for comparable work. Since their energy is derived from a rotating flywheel, the rating of their actual capacity is impractical. In general a medium-size press has the equivalent capacity of an 8,000-lb hammer. The largest press in use has a capacity equal to that of a 12,000-lb hammer. Their operating speeds vary inversely as their size and range from 125 strokes per minute for the smaller machines to 40 strokes per minute for the largest one.

11–19. Trimming. When the two drop-forging dies make contact in operation, the metal, in excess of that required to fill the die impressions, is forced between the faces of the dies into *gutters.* These are machined slightly below the surface of the dies. The metal forced into these gutters is known as *flash.* The forging is later *trimmed* by cutting off the flash by means of a sharp-edge die and punch on a mechanical press when the metal is either hot or cold; this is known as hot and cold trimming, respectively. Small multiple forgings made from a bar in one heat are usually trimmed when the metal is cold.

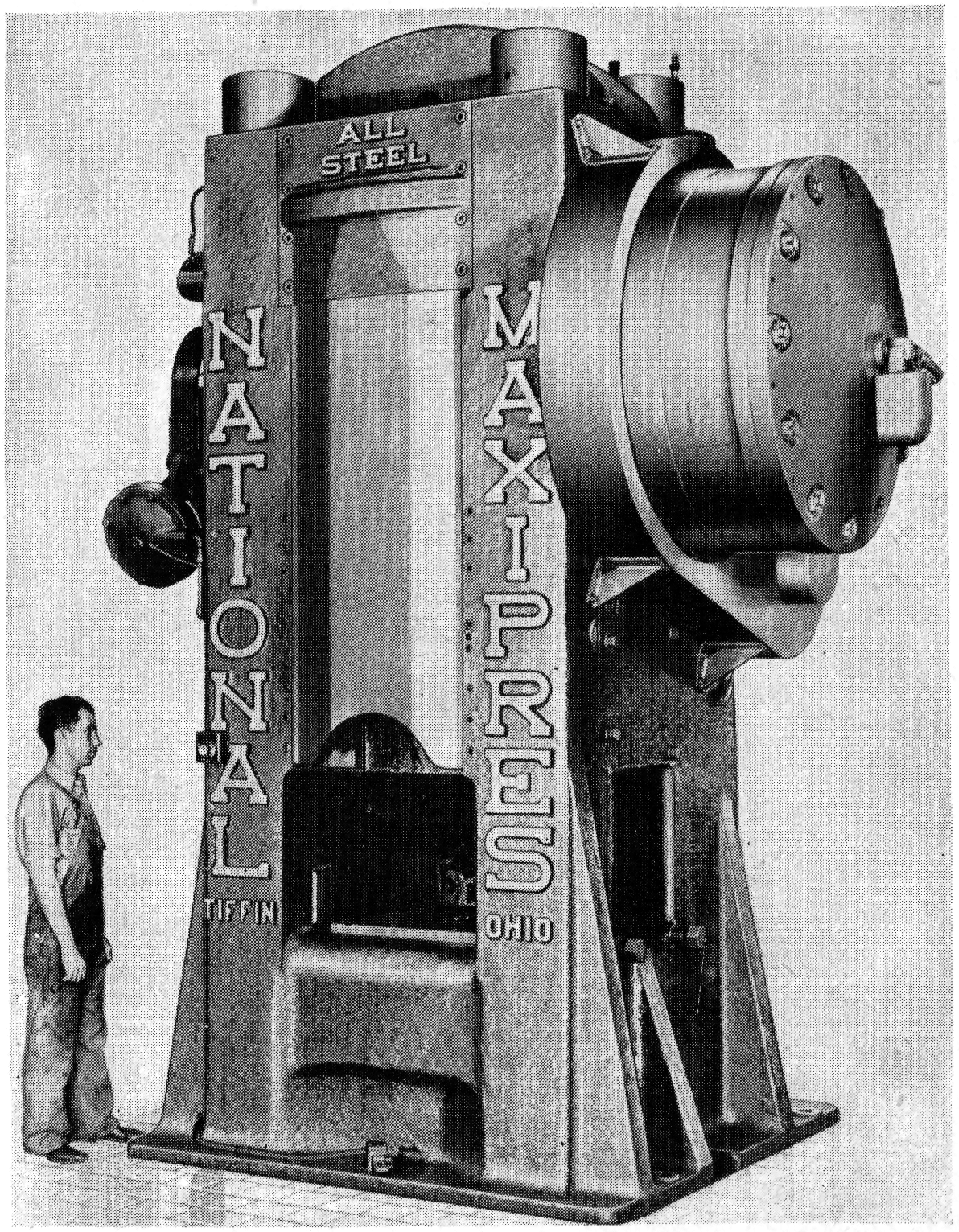


FIG. 11–28. A modern high-speed mechanical forging press. (Courtesy of National Machinery Co., Tiffin, Ohio.)

Because of increasing use of alloy steel forgings and the desire to prolong the life of the trimming dies, hot trimming is used to a much larger extent than is cold trimming. Alloy steels, which have a tendency to air-harden, make hot trimming almost mandatory. The trimming dies are usually made of carbon steel with a hard facing alloy welded along the cutting edges.

11–20. Shrinkage Allowance. In common with casting practice, provision must also be made in the dimensions of die impressions for the shrinkage of the forgings during cooling. This provision may be determined by multiplying the product of each desired dimension of the cold forging and the coefficient of expansion of the metal by the difference in the temperature between the finishing temperature of the forging and the average room temperature.

Example. General formula applied to the length of the die:

$$L' = L + l\,(T_2 - T_1)$$

L' = die dimension
L = length of forging
l = temperature coefficient of metal
T_2 = finishing temperature of forging
T_1 = room temperature

We solve for width and thickness by substituting W for L and T for L in the above formula.

11–21. Tolerance and Die Wear. A feature of modern production drop-forging practice is the economy effected by the reduced cost of machining forgings because of the closer tolerance and smaller draft with which they are now produced. The older practice which provided for a 7- to 10-degree draft is now reduced in many instances to as little as 1½ degrees. Machining production schedules require that automobile parts, such as connecting rods weighing from 2 to 4 lb, be furnished with a weight tolerance of less than one ounce, with a thickness tolerance on the ends of ±0.005 in. Many other parts, such as crankshafts, are forged with counterweights to equally close dimensions.

In order to meet the above conditions, a vigilant and rigid inspection must be maintained to check correct die alignment, forging temperatures and techniques, maintenance of equipment, and any other possible condition which might affect the tolerance of the forging. Since die wear means larger forgings and unavoidably increased machining costs, die dimensions are checked carefully, and the dies are replaced by new ones when necessary. As already pointed out, die life is governed by many factors which, combined, determine the production before replacement will be found necessary. It may be pointed out that in spite of the increasing demands for accuracy, manufacturers of forging equipment have made considerable progress in the design which provides for greater sturdiness, size, and efficiency of forging hammers and presses. Whereas 5,000 pieces were considered good production, today as many as 20,000 or more similar pieces are produced before a set of dies is replaced.

To the factors governing the proper grade and size of die block, which have been pointed out above, may be added others which govern the life or service of a die impression: (1) the temperature of the metal being forged; (2) the size of the hammer; (3) the type of forging made; (4) the properties of the metal being forged; (5) the manufacturing tolerances; and (6) the ability to avoid mismatching of dies through the proper maintenance of the hammer and alignment of the dies.

Forging dies vary widely in size as well as in analysis. They run from 3-in. cubes, weighing approximately 8 lb, to those which are used to forge rear axle truck housings, diesel crankshafts, propeller blades, and other large forgings.

11–22. Calculation of Stock. Since it is both practical and economical to use only the required amount of metal, it is frequently necessary to know, in view of the close tolerance now required on forgings, the volume of the metal which will be required. When forgings are of such complex shapes as to render calculations impossible or difficult, this determination may be made on a weight basis. In normally clean steel the change in volume during forging is negligible; therefore, computations of plane forgings may be made on a comparative volume basis, while others are made on a weight basis.

11–23. Rolling. Generally conceded to be the most productive process from a tonnage standpoint as well as the most economical, rolling is the most universal method of shaping and working ingots of steel. As there are many parts which cannot be made by casting, so there are many intricate shapes which can best be made by forging, while others best lend themselves to production by rolling.

Channels, I-beams, T- or Z-bars, angles, rails, plates, sheets, rods, and bars in all commercial sizes up to 60 ft in length are essentially rolled products and practically incapable of production by any other method.

11–24. Procedure in Rolling. In reduction, or shaping by hot-rolling, the metal passes between two or more rolls set above each other, revolving in opposite directions at the same peripheral speed, and spaced a distance equal to the amount of reduction or draft contemplated. To effect a reduction in the thickness or height, the metal as it enters the rolls is larger than the opening provided so that, when it passes between the rolls, it is reduced until it is practically equal to the distance between the rolls.

The amount of each reduction or draft depends upon the grade or analysis of the metal, its static resistance, its temperature, the power available in the rolls, and the ratio of roll diameter to the thickness of the piece. While large, smooth rolls grip the metal more easily and exert a greater pressure than those of smaller diameter, they, nevertheless, cause a greater lateral spread with correspondingly less elongation than do smaller rolls.

11–25. Heating for Rolling. Precautions and conditions governing the heating of steel for forging by other processes also apply to heating for rolling. Nearly always all large sections and ingots are worked from their permissible maximum temperature.

After attaining a certain state of solidification, an ingot is removed from the mold and immediately placed in a *soaking* pit, where it remains until it has attained a uniform temperature throughout. Soaking pits are rectangular furnaces, built either above or below ground level, which have a capacity for a number of ingots and are heated with coke oven, blast furnace, natural, or producer gas. Like the open-hearth, the soaking pit employs the regenerative principle of heat conservation, and the direction of gas flow into the furnace is changed every 15 or 20 min. From the soaking pit the ingot is transferred to power-driven roll conveyor tables, which bring it to the rolling mill.

11–26. Types of Rolling Mills. A rolling mill consists essentially of two or more chilled cast-iron, plain, or alloy cast-steel rolls mounted in housings above one another and axially parallel. One roll is usually placed in a stationary housing while the others may be adjusted up and down as required.

Rolling mills are identified (1) as either reversing or continuous, or (2) by the number of rolls set above one another and constituting a *stand.* A reversing mill is one in which the ingot is reduced to size by having its direction of travel reversed after each pass; it usually consists of one stand and two rolls. A continuous mill consists of a number of stands of 2-high mills, and the metal travels consecutively from one stand to the other until it is finished. Because a rolled section passes through several mills in succession, the roll speed must be increased at each stand to conform to the reduced thickness.

Depending on the number of rolls in a stand, mills are also known as 2-high, 3-high, 4-high, or cluster. A 2-high mill consists of 2 rolls, both of which are work rolls revolving in opposite directions and usually reversible. The 3-high mill consists of 3 work rolls, in which the upper and lower rolls are usually larger than the intermediate one. The top and bottom rolls rotate in the same direction while the middle one rotates in an opposite direction. By this arrangement the metal, supported on an elevating table, is led into the rolls on one elevation in one direction and returns between the upper and middle rolls on another elevation. Mechanical manipulators turn over or straighten the piece as required. A 4-high mill consists of 2 work rolls which are "backed up" by considerably larger rolls and is generally employed for the continuous production of flat plate and sheets. In a cluster mill, which is most frequently used for cold-rolling of sheets, the two work rolls are backed up by two much larger rolls because of the great strength and accuracy required. The arrangement of rolls is shown in Fig. 11–29. Plates, slabs, and bars finished with smooth edges are rolled in a *universal* mill, in which there are vertical and horizontal rolls.

Rods and small bars are rolled to size in a *merchant* mill which consists of a series of stands, and the metal is progressively reduced to size by a continuous series of passes. In one type of merchant mill, the metal is "looped" around a form on the floor and is led into the successive mills before it is completely out of the preceding ones.

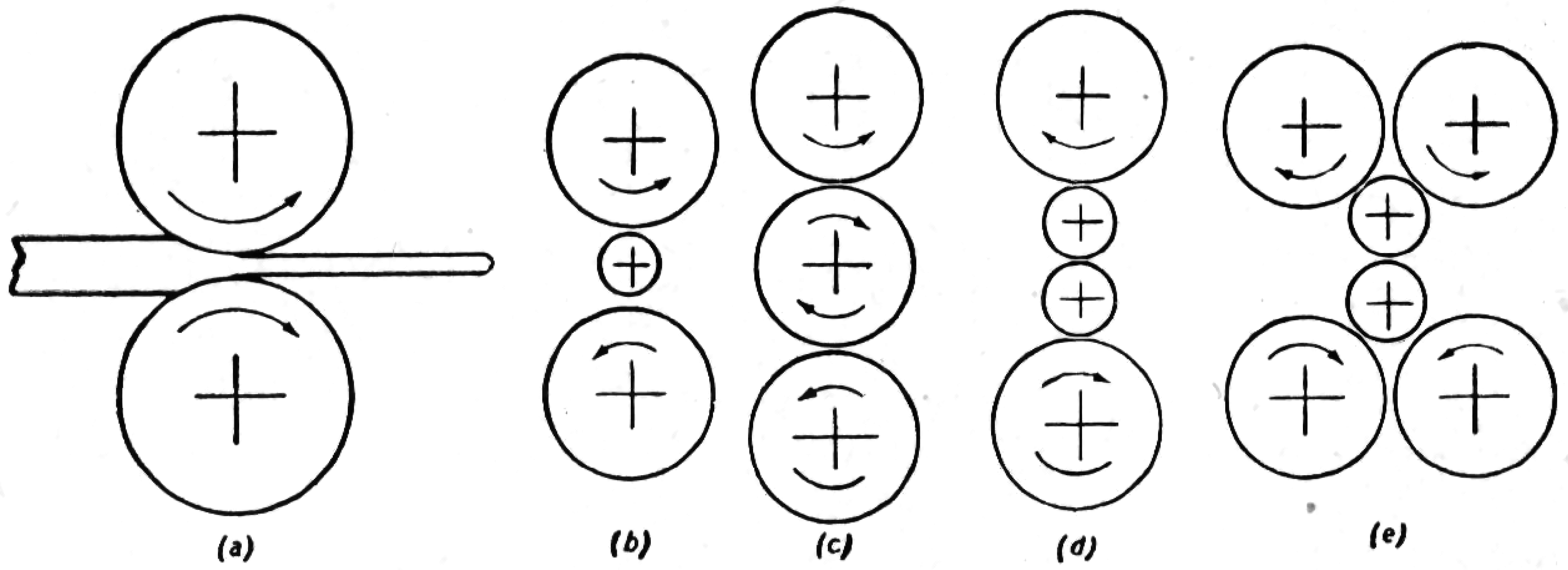


FIG. 11–29. At (*a*), arrangement of rolls on 2-high mill; at (*b*) and (*c*), 3-high mill; at (*d*), 4-high mill; and at (*e*), cluster mill.

The size of rolling mills is designated by the diameter of the rolls and their linear length, such as 30 by 48 in. The size of plate and sheet mills is determined by the maximum width of product the mills are capable of rolling.

Besides the various "shapes" mentioned, other products of the rolling mill are blooms, billets, bars, sheets, slabs, rods, plate, and strip. While there is no definite division between several of these terms as seen from the following definitions, the terminologies used are generally applied and accepted in mill practice.

A *bloom* may be a square, rectangular, or any semifinished shape having a thickness greater than 6 in.

A *billet* is a similarly shaped semifinished product not over 6 in. or smaller than 3 in. thick.

A *slab* is a rectangular section, with a width much greater than its thickness, which is intended for further rolling into sheet or plate.

Plates, *strip*, and *sheets* are finished or semifinished products of a plate, strip, or sheet mill. A plate has a minimum width of 6 in. and is not less than ¼ in. thick. Strip and sheet differ only in width—strip has a maximum width of 12 in. and is less than ¼ in. thick.

Rods are light bars of regular shape.

Shapes include all regular longitudinal sections, such as rails, channels, angles, etc.

11–27. Hot Forming of Tubes and Pipes. The manufacture of tubes and pipes consumes a substantial amount of rolled steel billets and strip. Square billets are converted by piercing and rolling into seamless tubing, while the strip, or skelp, as it is most commonly called when used for pipe, is first formed and then seam-welded by various methods.

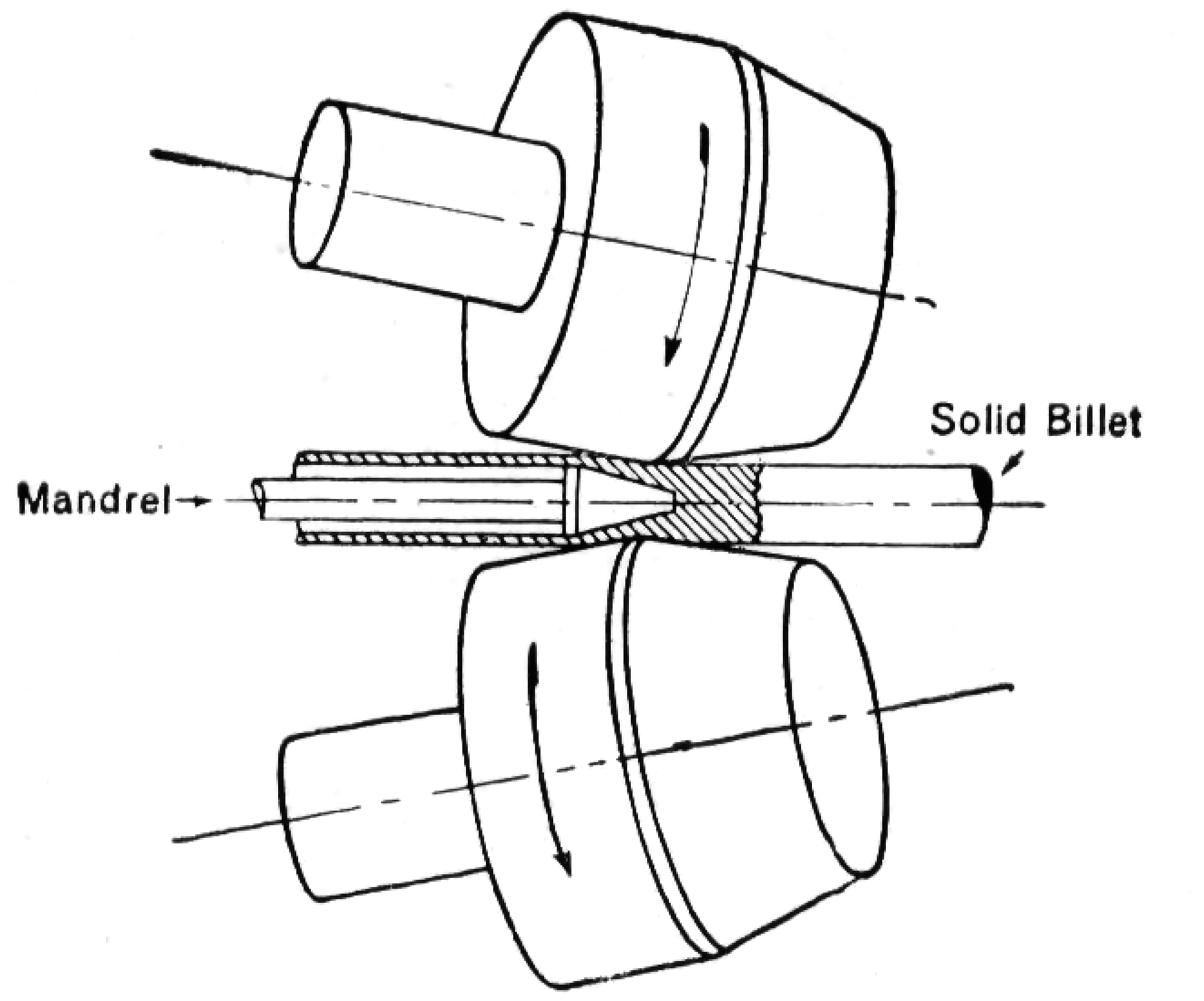


FIG. 11–30. Diagram of piercing operation, showing arrangement of rolls and mandrel and the principle of diagonal rolling employed in roll piercing.

11–28. Seamless Tubes. After the removal of all surface defects remaining or developed by rolling of the ingot, square billets are reheated and rolled into rounds of a diameter and length required for the tube. While still hot, the billets are centered or punched on one end to a depth of about 1 in., after which they are reheated to a white heat, preparatory to the formation of the tube by rolling over a piercing mandrel whose axis is in line with that of the billet. Because of their shape and the relative angle at which they are set, the rolls rotate the billet rapidly and draw it forward over the mandrel until the solid metal is penetrated throughout its axial length and the metal is displaced from the center to the tube wall. Thus, the billet is converted into a rough, thick-walled, seamless tubing not particularly true to size. A diagram illustrating this operation is shown in Fig. 11–30.

In a subsequent operation called *reeling*, the tube is elongated, the wall thickness and the diameter are reduced, and a smooth inner and outer surface are produced.

Large tubes are produced by expanding the diameter and decreasing the wall thickness by hot-rolling the smaller tube over an expanding mandrel with specially designed rolls.

Seamless tubing is made in all sizes up to 28 in. O.D. and in lengths exceeding 40 ft. In contrast to butt and lap welded pipe, which are generally made of low-carbon steel in the range 0.08 to 0.12 per cent carbon, and electrically welded pipes, which sometimes contain 0.30 per cent carbon, no such restrictions on composition are imposed on seamless tubing. Seamless tubes are manufactured of plain carbon steels ranging in composition from 0.10 to 0.70 per cent carbon and of alloy steels of a wide variety of compositions, including the stainless 18 per cent chromium, 8 per cent nickel alloys, and other grades of chromium steels used in refineries and oil cracking installations.

The adaptation of the hot piercing and rolling process to the production of 75 mm gun barrels during World War II has resulted in a phenomenal increase in production. The former practice of drilling the solid billet which required up to 6 hr is now performed in 15 sec by hot piercing.

Steel containers for high-pressure gases such as oxygen, nitrogen, carbon dioxide, ammonia, hydrogen, compressed air, and acetylene are made by cupping of disks, or by piercing and subsequently forcing heated billets through a series of drawing dies of successively smaller diameter, thus increasing their length and reducing the wall thicknesses.

11–29. Welded Pipe. Welded pipe is made of low-carbon steel strip or skelp rolled to the required thickness and width on any plane roll mill.

It has long been the practice to weld pipe seams by overlapping beveled edges of the skelp or by butting square edges. These processes are known as lap and butt welding. Recent trends indicate a gradual discontinuance of the lap process because of manufacturing difficulties. Butt welded pipes, however, are satisfactorily made in sizes ranging from 1/8 to 3 in. nominal diam for a wide variety of uses and strength—such as standard, extra strong, and double extra strong, depending on wall thickness—and in length varying from 20 ft standard to 40 ft.

The skelp for butt welding is charged into furnaces capable of heating it to its welding temperature after one end has been slightly formed to enable it to be placed through the die and gripped with the draw tongs. When the metal has reached welding heat in the furnace, it is drawn through a bell-shaped die which bends the skelp and welds the edges at the same time. Fig. 11–31 shows the skelp being drawn through a die.

11–30. Electric Resistance Welded Pipe. Tube suitable for aircraft and boilers of plain carbon and alloy steels may be made by the seamless process or by the resistance welding method, which is now widely used for these purposes. Skelp for the latter method is either drawn through a die or progressively bent by a series of rolls until the tube is formed as shown in Fig. 11–32. It is welded by being drawn forward while the edges, which become heated by resistance to the conduction of current between the two circular water-cooled electrodes, are pushed together by the pressure rolls. A later operation removes a small burr from both the inside and outside surface.

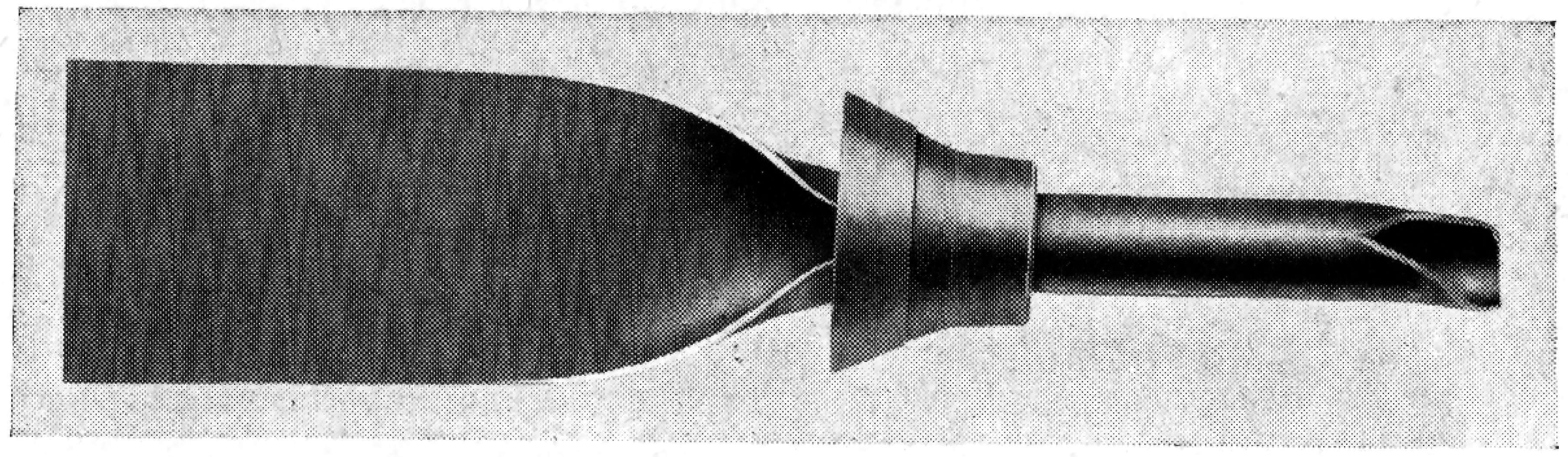


FIG. 11–31. Welding bell or die used in drawing butt weld pipe, showing piece of skelp partly drawn into pipe. (Courtesy of National Tube Co., Pittsburgh, Pa.)

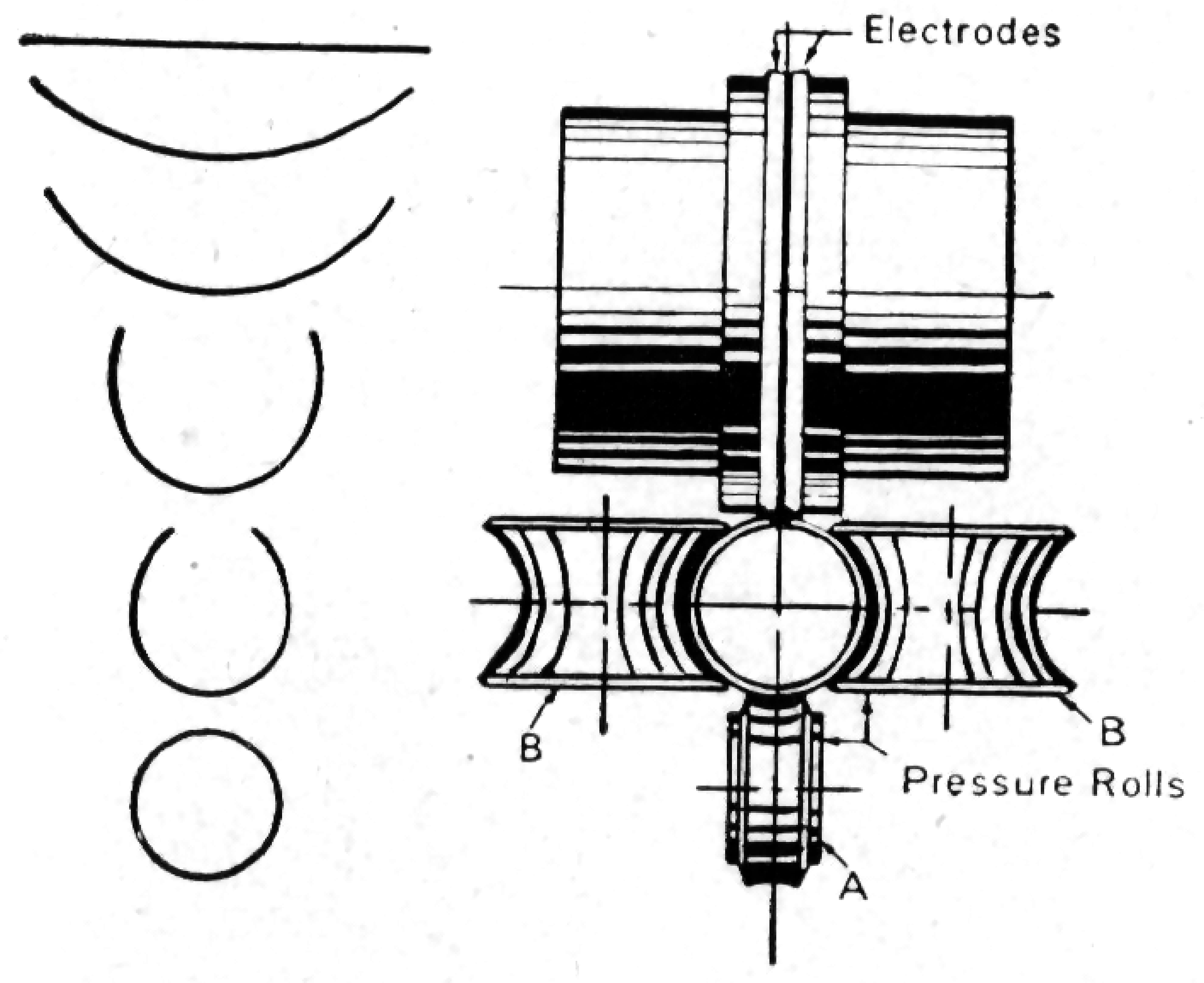


FIG. 11–32. Application of rolls on both sides and beneath welding electrodes force heated tube edges together to form a weld. By gradually forming flat steel into tubular shape, as shown at left, undue strain of material is avoided.

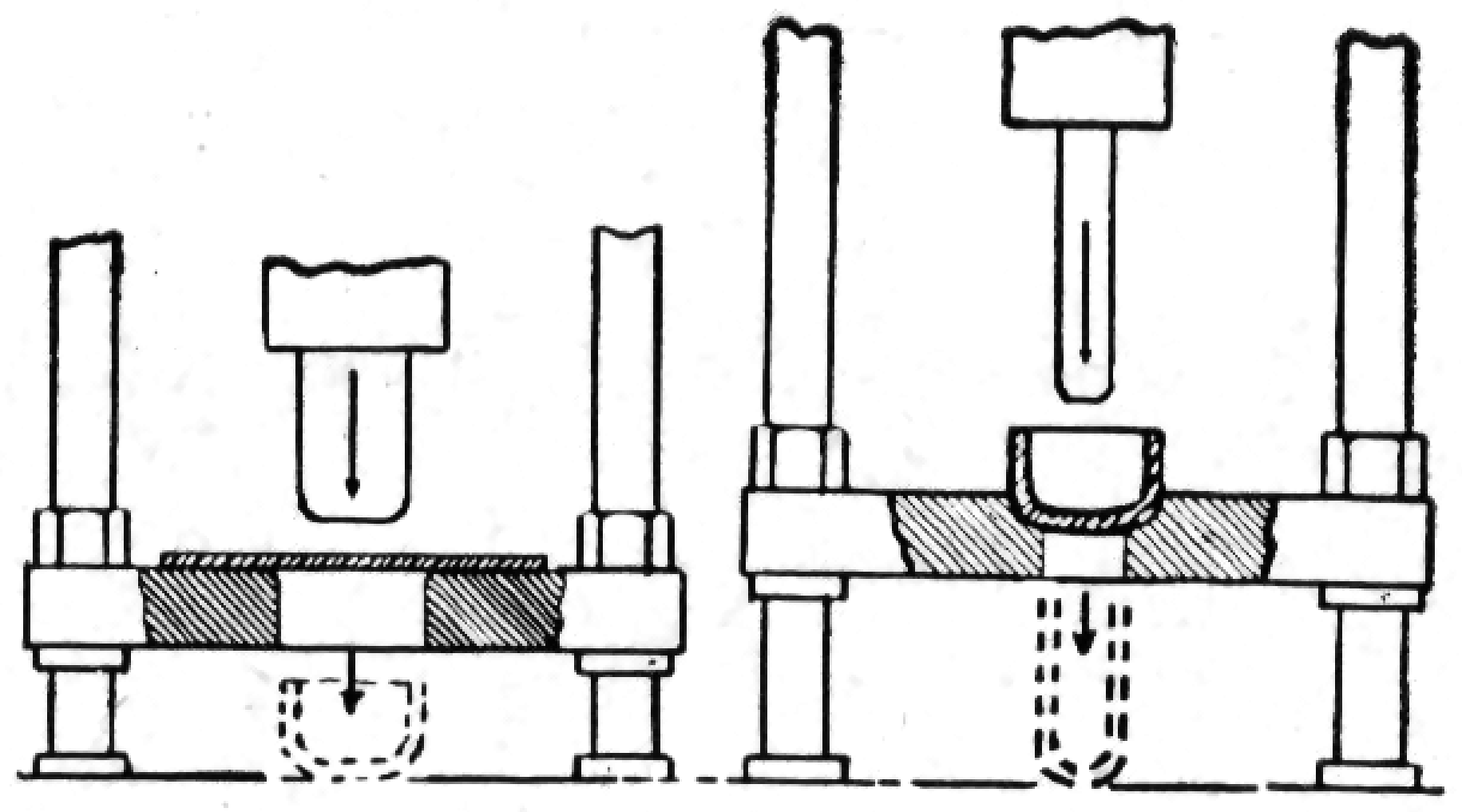


FIG. 11–33. Diagrams of first (left) and second (right) cupping operations

Boiler tubes 4 in. in diam are welded by this method at a rate of 30 to 40 fpm, while tube up to 1½ in. diam is welded at a rate of 100 fpm.

Electrically welded tubing withstands flattening, expanding, or axial crushing in the cold state without rupture or failure of weld. Other properties are also similar to those of a seamless tube of the same analysis.

11–31. Cupping Process. Tubular products in short lengths, such as brass or steel shells or cartridge cases, are produced while cold by the progressive drawing of disks containing the necessary amount of metal in a series of dies in which the cup-shaped metal is progressively reduced in external diameter and elongated while the wall thickness is reduced. This method, shown in Fig. 11–33, is called cupping or drawing and is performed by mechanical or hydraulic processes.

11–32. Cold-Working of Metals. In common with most commercial metals and alloys, steel possesses sufficient ductility to enable its plastic deformation to be carried out in both the hot and cold state. Large reductions are made, as described, while the metal is in a highly plastic state or above the A_1 temperature shown in Fig. 9–6. All mechanical work performed on steel above this temperature is known as *hot* work, in contrast to *cold* work when the deformations are performed below the critical temperature.

Since in all hot-working a partial or complete recrystallization removes the induced stress, cold-working consists more specifically of working at such low temperatures as to leave the metal in substantially a state of stress, commensurate with the amount of deformation and other factors involved in cold-working, as pointed out later.

Cold-working embraces a wide variety of finished and semifinished parts involving the use of a great diversity of equipment and operations such as shearing, bending, punching, swaging, etc. Since these are strictly part-forming or fabrication, rather than metal manufacturing processes, the discussion following is confined to the manufacturing phase of production. The principal methods of cold-working are drawing and rolling.

11–33. Objectives of Cold-Working. Cold-working consists of subjecting previously hot-finished bars, sheets, or wire to a definite and variable amount of plastic deformation, usually at room temperature or specifically below the recrystallizing temperature to obtain certain desirable results or characteristics in the metal. The principal objectives are (1) to obtain products finished to close tolerances, (2) to obtain surfaces free of oxide or discoloration, (3) to produce better machinability, (4) to improve the yield and tensile strength, and (5) to increase hardness.

The close dimensions obtainable by cold-working at or near normal temperatures are difficult or impossible to achieve by hot deformation, because of the shrinkage of the metal during subsequent cooling. The relative accuracy and physical characteristics of cold- and hot-finished round bars is shown in Table 11–5. For fabrication processes, these close tolerances are a valuable asset, because operations may be performed and holes may be drilled or dies made to accommodate the metal with reasonable assurance of fit, since all cold-worked products are finished slightly undersize as shown in Table 11–6.

TABLE 11–5

SIZE ACCURACY OF COLD-DRAWN VERSUS HOT-ROLLED*

Size (In.)	Variation (In.)	Tolerance (In.)	Out of Round (In.)
½ Rd. H.R.	0.492 to 0.508	± 0.008	0.012
½ Rd. C.D.	0.500 to 0.498	0.002 minus	0.001
1 Rd. H.R.	0.990 to 1.010	± 0.010	0.015
1 Rd. C.D.	1.000 to 0.998	0.002 minus	0.001
2 Rd. H.R.	1.978 to 2.022	± 0.022	0.030
2 Rd. C.D.	2.000 to 1.997	0.003 minus	0.0015
3 Rd. H.R.	3.000 to 3.078	0.078	0.046
3 Rd. C.D.	3.000 to 2.996	0.004 minus	0.002

Transactions ASM, Vol. 25 (March 1937), p. 108.

Differences of even greater proportions exist between hot-rolled and cold-drawn hexagons, squares, flats, and special sections.

TABLE 11–6

STANDARD MANUFACTURING TOLERANCES*

Cold-Finished Steel Bars And Shafting
(0.50% Carbon And Less)

Rounds	0.30% Carbon Or Less	0.31% To 0.50% Carbon
1 inch or under	0.002 inch minus	0.003 inch minus
1 1/16 to 2 inch inc.	0.003 inch minus	0.004 inch minus
2 1/16 to 4 inch inc.	0.004 inch minus	0.005 inch minus
4 1/16 to 6 inch inc.	0.005 inch minus	0.006 inch minus
6 1/16 to 7 inch inc.	0.006 inch minus	0.008 inch minus

Standard Manufacturing Tolerances On "HEAT TREATED" Bars Are Double Those Shown

Hexagons	0.30 per cent Carbon Or Less	0.31 per cent To 0.50 per cent Carbon
Up to 0.3 inch inc.	0.002 inch minus	0.003 inch minus
Over 0.3 inch to 1 inch inc.	0.003 inch minus	0.004 inch minus
Over 1 inch to 2½ inch inc.	0.004 inch minus	0.005 inch minus
Over 2½ inch to 4 inch inc.	0.005 inch minus	0.006 inch minus

Squares	0.30 per cent Carbon Or Less	0.31 per cent To 0.50 per cent Carbon
Up to 0.3 inch inc.	0.003 inch minus	0.004 inch minus
Over 0.3 inch to 1 inch inc.	0.004 inch minus	0.005 inch minus
Over 1 inch to 2½ inch inc.	0.005 inch minus	0.006 inch minus
Over 2½ inch to 4 inch inc.	0.006 inch minus	0.008 inch minus

Flats	Narrower Than 1½"		1½" To 4" Wide		Over 4" To 6" Wide	
Thickness	0.30 per cent Carbon Or Less	0.31 per cent To 0.50 per cent Carbon	0.30 per cent Carbon Or Less	0.31 per cent To 0.50 per cent Carbon	0.30 per cent Carbon Or Less	0.31 per cent To 0.50 per cent Carbon
Up to 0.3 inch inc.	0.003 inch minus	0.004 inch minus	0.005 inch minus	0.006 inch minus	0.008 inch minus	0.010 inch minus
Over 0.3 inch to 1 inch inc.	0.004 inch minus	0.005 inch minus	0.005 inch minus	0.006 inch minus	0.009 inch minus	0.012 inch minus
Over 1 inch to 2½ inch inc.	0.005 inch minus	0.006 inch minus	0.006 inch minus	0.008 inch minus	0.010 inch minus	0.012 inch minus

The tolerances on flats apply to thickness as well as width, and the width dimension determines the tolerance

THE STANDARD MANUFACTURING TOLERANCES PROVIDE FOR UNDERSIZE VARIATION ONLY

Transactions ASM, Vol. 25 (March 1937), p. 108.

11–34. Procedure in Cold-Working. The hot-finished metal, prior to cold-working, is first pickled in a 3 to 8 per cent sulphuric acid solution to remove all scale on the surface. This is followed by washing in water and immersion in slaked lime to neutralize any remaining acid and to lubricate the metal during its processing. In conjunction with the characteristics of the processes, this prior condition produces a scale-free and bright surface on cold-worked steel suitable, without further polishing, for many machine parts.

Because of the closer tolerances, the scale-free surface, and the slight increase in hardness, cold-worked bars are preferred over hot-finished bars for machine operation, particularly for automatic screw machine work.

In addition to increasing hardness, cold-working also increases both the yield and tensile strength, but with a commensurate decrease in ductility. A comparison of the mechanical properties of hot- and cold-drawn steel of various analyses is shown in Table 11–7.

TABLE 11–7

REPRESENTATIVE PHYSICAL PROPERTIES; HOT-ROLLED VERSUS COLD-DRAWN*

Grade	Size (In.)	Yield Point	Tensile Strength	Elong. (Per Cent)	Red. (Per Cent)	Brinell
SAE 1112.........	$1\frac{1}{16}$ Rd. H.R.	40,480	64,780	35.0	53.0	131
SAE 1112.........	1 Rd. C.D.	82,460	89,700	17.0	43.5	187
SAE 1020.........	$1\frac{1}{16}$ Rd. H.R.	38,240	59,100	37.0	62.0	118
SAE 1020.........	1 Rd. C.D.	75,120	82,750	20.0	51.7	156
SAE 1035.........	$1\frac{1}{16}$ Rd. H.R.	45,240	77,100	35.0	48.0	149
SAE 1035.........	1 Rd. C.D.	87,240	94,240	15.2	41.2	197

Transactions ASM, Vol. 25 (March 1937), p. 108.

The above cold-drawn values are obtained on hot-rolled bars cold-drawn at $\frac{1}{16}$ in. draft amounting to 11.4 per cent in regular commercial production.

The degree to which cold-working influences the mechanical properties is a function of (1) the amount of cold-work, (2) the temperature at which it is done, (3) the initial grain size, and (4) the analysis of the metal—relatively a greater increase in both yield and tensile strength is noted in low-carbon than in the high-carbon or alloy steels.

11–35. Processes in Cold-Working. As mentioned before, the principal cold-working processes are drawing and rolling. These processes involve the stretching or elongation of the metal by drawing through a tapered orifice or die or by subjecting to the roll action or squeeze of suitable rolls. Since they accentuate all surface irregularities and affect the initial structure, both operations necessitate careful control over both the internal and external condition of the metal, if a high quality product is desired.

After being *pointed* or reduced for a short distance on the end the bar is put through the die until it can be gripped by tapered jaws attached to an endless block chain through which power is applied. These jaws draw the bar through the die at variable speeds as governed by size, shape, grade of material, quality of finish, and the permissible amount of reduction. The drawing speed varies from about 60 fpm for bar stock to 300 fpm for small diameter wire. A number of bars or wire may be drawn simultaneously, and a fine wire may require several draws. Wire is drawn through the die by a rapidly revolving drum, on which the wire is coiled. The reduction in diameter or draft, also governed by the size of section, shape, chemical analysis, etc., varies from 1/64 (0.015625) to ⅛ (0.125) in. and is seldom over 15 per cent of the diameter. The die inserts in the die block are sintered carbides, white cast-iron, hardened tool steel, or for hard, fine wire, commercial diamonds.

11–36. Types of Steels Used. Provided it is in the annealed condition (preferably spheroidal pearlite), practically all grades of both carbon and alloy steels can be cold-drawn or cold-rolled. However, the steels most commonly used are SAE 1112, 1120, 1020, 1035, 1040, 1045, x1314, x1315, and x1335.

11–37. Cold-Rolling. For the cold-finishing of flat surfaces, such as sheets and strips, the pickled, washed, and limed oversize hot-rolled plates are subjected to a further rolling action at room temperature by passing between the rolls, as shown in Fig. 11–29 at (*d*).

Besides solid bars, wire, and sheets, seamless tubing is also cold-finished for the purpose of controlling the dimensions of both the outside and inside diameter.

11–38. Drawing of Seamless Tubes. As in the cold-drawing of wire and rods, the tube is sufficiently reduced in diameter to permit its entrance into the die and its being gripped on the draw side. Tubes are usually reduced by being drawn through the die over a bar or mandrel of the correct size to control the inside diameter. When the wall is thick, relative to the diameter, or when the inside diameter need not be controlled closely, the tube may be drawn without the mandrel by a process known as *sinking*, when reductions of from 20 to 35 per cent may be made in one pass, depending on the wall thickness. When a mandrel is used, the customary reduction per pass varies from 30 to 50 per cent. For the drawing of small tubing, such as hypodermic needles of approximately 0.025 in. O.D. and 0.005 in. wall thickness, a hard-drawn, high-carbon steel wire of uniform diameter is inserted in the tube to maintain correct diameter and to produce a burnished surface when pulled out.

Although round tubes and bars are most frequently drawn, nevertheless, square, hexagon, elliptical, and other shapes can also be produced in suitable dies.

For very accurate dimensions, brighter finish, and straightness for specific applications, cold-rolling or drawing may be supplemented by grinding, turning, and polishing.

11–39. Metallurgical Aspects of Cold-Working. Because of the relatively lower ductility of alpha ferrite, as compared to austenite, the grain refinement resulting from hot mechanical work is not duplicated by cold-working. The influence of cold deformations on the grain structure is to cause transcrystalline fragmentation and definite orientation in contrast to the equiaxial grains after hot-working. However, unless drastic reductions are made, as in producing small wire or thin sheets, no structural distortion is apparent except in carbon steels of over 0.50 per cent carbon, in which case slight indications of grain elongation can be detected. The tendency to grain distortion, which prevails even with small draft, induces internal stress whose magnitude determines the sensitivity of the metal to subsequent annealing or recrystallization.

TABLE 11–8

Influence of Cold-Working on Mechanical Properties of Wrought Aluminum Alloys

Alloy and Temper*	Yield Point (Psi)	Tensile Strength (Psi)	Elongation 2 In.	
			Sheets (1/16 In. Thick)	Rounds (½ In. Diam)
2S–O (annealed)	5,000	13,000	35	45
2S–O ¼ hard	13,000	15,000	12	25
2S–O ½ hard	14,000	17,000	9	20
2S–O ¾ hard	17,000	20,000	6	17
2S–O Hard	21,000	24,000	5	15
3S–O (annealed)	6,000	16,000	30	40
3S–O ¼ hard	15,000	18,000	10	20
3S–O ½ hard	18,000	21,000	8	16
3S–O ¾ hard	21,000	25,000	5	14
3S–O Hard	25,000	29,000	4	10
52S–O	14,000	29,000	25	30
52S–O ¼ hard	26,000	34,000	12	18
52S–O ½ hard	29,000	37,000	10	14
52S–O ¾ hard	34,000	39,000	8	10
52S–O Hard	36,000	41,000	7	8

Designated by Aluminum Company of America.
Note: 2S = 99.9 per cent Al; 3S = 1.20 per cent Mn, balance Al; 52S = 2.5 per cent Mg, 0.25 per cent Cr, balance Al.

Where ductility with moderate tensile and yield strength is desirable, low-carbon steel wire is given a low temperature anneal after cold-drawing, by heating to between 700 and 1000F. Where advantage is to be taken of the high tensile properties, the wire must be used in the condition as drawn.

11–40. Recrystallization. While it is generally agreed that working below the critical temperature defines cold-working of steel, it is more correctly defined as the plastic deformation of the metal below its recrystallizing temperature. Below this temperature, all metals become strain-hardened when mechanically deformed; above this temperature, the metals anneal themselves and therefore cannot be work-hardened. This characteristic holds for both ferrous and nonferrous metals which do not undergo an allotropic transformation similar to steel.

Several factors affect the recrystallization (or self-annealing) temperature of cold-worked metals. This temperature is generally lowered by each of the following factors: (1) the greater the amount of cold-working, (2) the lower the temperature of cold-working, (3) the smaller the original grain size, (4) the purer the metal or the fewer the inhibitors to grain growth, and (5) the longer the time at temperature. Only metals which recrystallize above normal temperatures are capable of strain-hardening. Besides steel, these include copper, aluminum, nickel, magnesium, and their alloys. Because their recrystallization occurs at, or below normal temperatures, tin, zinc, lead, and cadmium cannot be strain-hardened materially by cold-working.

TABLE 11–9

Tempers and Hardness of Some Cold-Rolled Copper-Zinc Alloys

Reduction by Cold-Working		Temper Brass Practice	Average Rockwell Hardness (1/16-In. Ball × 150 Kg Load X Red Figures)						Nominal Ultimate Tensile Strength (High Brass), Psi	General Elongation (High Brass), Per Cent in 2 In.
B. & S. Gauge Nos.	Per Cent (Approximate)		Brass		Nickel-Silver		Phosphor-Bronze			
			1	3	4	5	6	7		
Annealed	0	Soft	..	..	..	..	..	..	47– 49,000	67
1	10	¼ hard	..	59	..	..	..	..	51– 53,000	46
2	20	½ hard	69	67	50	66	39	60	57– 60,000	28
3	30	¾ hard	74	..	..	..	..	..	66– 68,000	17
4	40	Hard	82	..	56	72	62	75	70– 77,000	11
6	50	Extra-hard	87	..	..	76	69	..	84– 86,000	10
8	60	Spring	90	..	..	..	73	81	94– 98,000	9
10	70	Extra-spring	..	..	..	..	..	82	101–108,000	8

Typical mechanical properties of aluminum sheets after cold-working various amounts are given in Table 11–8. Those of copper-zinc alloys are given in Table 11–9.

QUESTIONS AND PROBLEMS

1. List the most common objectives of the hot mechanical working of metals.
2. What properties of a metal determine its ability to withstand severe plastic deformation?
3. Explain what occurs, crystallographically, when an external force causes metal displacement or plastic flow.
4. Discuss the cause of flow lines in mechanically worked steel.
5. In order to obtain equal strength in all the teeth, should a gear blank be upset by an applied force parallel with, or perpendicular to, the axial length of the cylinder
6. Assume a plate ¼ x 3 x 14 in. is blanked or cut from a sheet so that the longer dimension is in the direction of the rolling of the sheet. If the four edges are bent 90 degrees while cold, which edges may have the greater tendency to crack during bending?

7. What factors condition the heating time of metals for forging?
8. Give reasons why wrought metals are generally superior in mechanical properties to similar metals in the cast condition.
9. List the processes by which metals may be mechanically worked.
10. Compare steam drop and board drop hammers as to efficiency, potential energy, size, and versatility.
11. Give reasons why it is customary to require the ratio given between the weight of hammer bases and the moving parts.
12. Discuss the influence of velocity of impact on the plastic deformation of metal.
13. Compute the potential energy of a steam drop hammer with a cylinder diameter D of 15 in., steam pressure S of 90 psi, length of stroke L of 30 in., weight of moving or reciprocating parts W of 20,000 lb (area of cylinder $\times S + W) L$.
14. What are the advantages of hydraulic presses over steam hammers for producing large forgings?
15. What type of work is generally performed on a forging machine?
16. Discuss the three basic rules of upset forging.
17. Compare casting and die-forging.
18. Compute the length, width, and depth of a drop-forging die impression for producing a forging of the following dimensions: length 14 in., width 2.75 in., thickness 1.75 in. Assumed room temperatures—80F. Forging finishing temperature—1950F.
19. List the factors influencing die life.
20. Under what conditions may forging cause a reduction in the volume of a metal?
21. Describe the various types of rolling mills.
22. Define a "bloom," "billet," "skelp," "slab," "strip," "sheet."
23. Define "cold-working."
24. Discuss the objectives and structural results of cold-working metals and alloys.
25. Why are cold-rolled parts finished with a minus tolerance?
26. In what respects is draft as applied to cold-worked products different from draft as applied to drop-forging dies?
27. Assume two steels in the same condition are reduced by cold-rolling an equal amount; one steel contains twice as much C as the other. Which of the two would show the greater percentage increase in tensile strength, yield strength, and hardness?
28. What is the structural mechanism of recrystallization of cold-worked metals?

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CHAPTER 12

WELDING PROCESSES, EQUIPMENT, AND APPLICATIONS

12–1. Definition. To weld is to effect a homogeneous bond between two or more components while the metals are in a highly plastic or fusion state, with or without the aid of mechanical pressure.

12–2. Classification. The various welding processes are divided into two general groups, which are known as resistance and fusion, or pressure and nonpressure, respectively, according to whether an external force or pressure in addition to heat is needed to properly execute the weld. The principal divisions of these two groups are given in the diagram, Table 12–1.

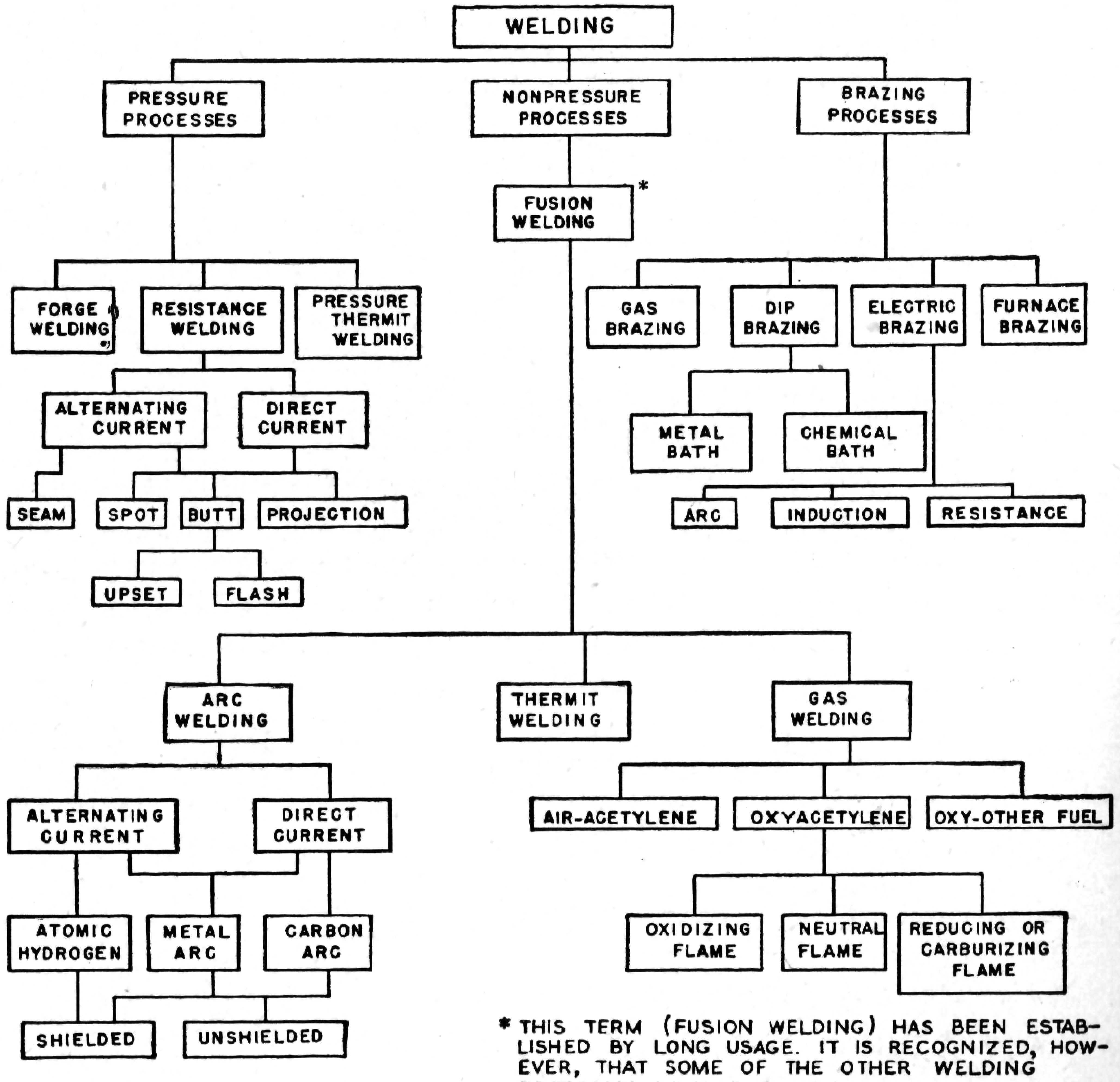
12–3. Introduction. The dual necessity of preserving the mechanical and the metallurgical characteristics of the metals while applying intensely localized heat to bring them to their respective welding temperatures often gives rise to problems which require some knowledge of design as well as of metallurgy, if welding is to be successfully employed as a means of fabrication. These problems, however, are capable of solution in whole or in part by the adoption of fabricating procedures and designs appropriate to the peculiarities of each type of metal. Metals of low melting point, those of high or low coefficient of expansion or of high or low thermal conductivity, those whose oxides are easy or difficult to reduce, those which may be susceptible to corrosion or decay adjacent to the weld, and those which are disproportionately weak (hot short) at the welding temperatures or are lacking in ductility, all demand consideration if satisfactory results are to be obtained.

The phenomenal expansion of welding for engineering purposes in very recent years can be ascribed to many causes too numerous to study here. Among the principal ones are (1) industrial demands for increased production coupled with economy and dependability, (2) development of and use of shielded arc welding, (3) enlarged capacities of pressure welding equipment with improved techniques for welding various metals of practically any thickness, (4) the use of oxygen-cutting machines for cutting parts preparatory to welding, (5) the furnishing by steel mills and other producers of special shapes suitable for welding.

12–4. Forge Welding. The beginning of the twentieth century found but one method whereby metals could be welded—the blacksmith forge process—and this could be applied only to the welding of wrought iron and low-carbon steel of relatively small size. A broken cast-iron machine part could not be repaired by welding and, therefore, it found its way into the scrap heap, eventually to contribute to the making of a new one. By now forge welding has largely been superseded by other

TABLE 12–1

MASTER CHART OF WELDING PROCESSES


WELDING
PRESSURE PROCESSES
NONPRESSURE PROCESSES
BRAZING PROCESSES
FUSION WELDING *
FORGE WELDING
RESISTANCE WELDING
PRESSURE THERMIT WELDING
ALTERNATING CURRENT
DIRECT CURRENT
SEAM
SPOT
BUTT
PROJECTION
UPSET
FLASH
GAS BRAZING
DIP BRAZING
ELECTRIC BRAZING
FURNACE BRAZING
METAL BATH
CHEMICAL BATH
ARC
INDUCTION
RESISTANCE
ARC WELDING
THERMIT WELDING
GAS WELDING
ALTERNATING CURRENT
DIRECT CURRENT
ATOMIC HYDROGEN
METAL ARC
CARBON ARC
SHIELDED
UNSHIELDED
AIR-ACETYLENE
OXYACETYLENE
OXY-OTHER FUEL
OXIDIZING FLAME
NEUTRAL FLAME
REDUCING OR CARBURIZING FLAME

* THIS TERM (FUSION WELDING) HAS BEEN ESTABLISHED BY LONG USAGE. IT IS RECOGNIZED, HOWEVER, THAT SOME OF THE OTHER WELDING PROCESSES INVOLVE FUSION.

Welding Handbook (1942 ed.).

processes adaptable for repairing or fabricating all commercially useful metals of almost unlimited size.

Forge welding consists of heating the parts, after they have been prepared or scarfed, in a forge or furnace fired with coal, coke, gas, or oil, to a temperature just below incipient fusion; then placing the parts together and uniting them by applying pressure or hammering quickly. A properly made forge weld, which also includes subsequent normalizing, develops physical properties equal to those of the base metal. The temperature to which those parts adjacent to the weld have been subjected, however, causes crystalline grain growth, which results in failure in these regions unless the condition is remedied by normalizing.

12–5. Thermit Welding. Since the discovery of the great affinity of aluminum for oxygen, this metal has been used extensively to reduce or deoxidize metallic oxides or ores to produce commercially pure metals such as ferrochromium, ferromanganese, ferrovanadium, and others. In a similar manner the oxides of iron may be reduced according to equation: $8Al + 3Fe_3O_4 \rightarrow 9Fe + 4Al_2O_3$ or $2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3$. In this reaction, pure iron is liberated, accompanied by a very considerable evolution of heat.

In thermit welding a mixture of finely divided aluminum and iron oxide, Fe_3O_4, in the form of hammer scale, is placed in a heavily lined conical crucible in an amount corresponding to the size of the weld to be made. When all the preliminary operations are completed and the weld is ready to be made, the mixture is ignited by the flare of a match placed in the midst of a small amount of metallic aluminum, magnesium powder, or barium peroxide. Once started, the reaction proceeds rapidly throughout the mass, producing metallic iron at a temperature of about 4800F and aluminum oxide which rises to the surface as a slag. The crucible is then tapped by displacing a projecting pin in its lower end which permits the superheated metal to flow into a mold and fuse with the base metal.

Modification of the analysis of plain thermit may be obtained by the addition of alloys, such as nickel or manganese, which increases the strength of the welds. Thermit welding of gray cast-iron may also be done with a mixture consisting of additions of mild steel and ferrosilicon added to plain thermit just prior to tapping.

12–6. Preparation of Parts to Be Welded. The parts to be welded are first aligned with a provisional gap between them varying from ¼ to over 2 in., according to the size of the section. Around the parts to be welded is molded a collar of plastic yellow wax of the size and shape of the reinforced collar desired on the finished weld. This collar constitutes a pattern within a mold of high-grade silica sand built around the parts in which are placed pouring gates, heating gates, and risers as required by the size of the parts and the volume of thermit used. A cross-section of a mold is shown at (*b*) in Fig. 12–1. Through the heating gates, the joint is then carefully preheated with a kerosene, gasoline, or gas-air torch. This heating is continued until the mold is thoroughly dry, the metal has attained a dull red color, and the wax has been burned out. The heating gates are then plugged with baked sand cores, the crucible is tapped, and the superheated metal fills the mold and fuses with the base metal, while the oxide of aluminum remains in the basin at the top of the mold. When sufficiently cool, the mold is destroyed and the weld is cleaned. Provided working conditions allow, the metallic collar remains for reinforcement. It may, however, be machined off.

The thermit reaction is nonexplosive and the mixture is inert below 2200F. The process is especially adapted for welding ferrous metals of large dimensions for machines and ships. Welds requiring up to two tons of thermit have been made. During World War II, extensive application was made of this process in the fabrication of large sections of cast-steel for stern posts of ships of the merchant marine, for which about 900 lb of thermit was required for each weld.

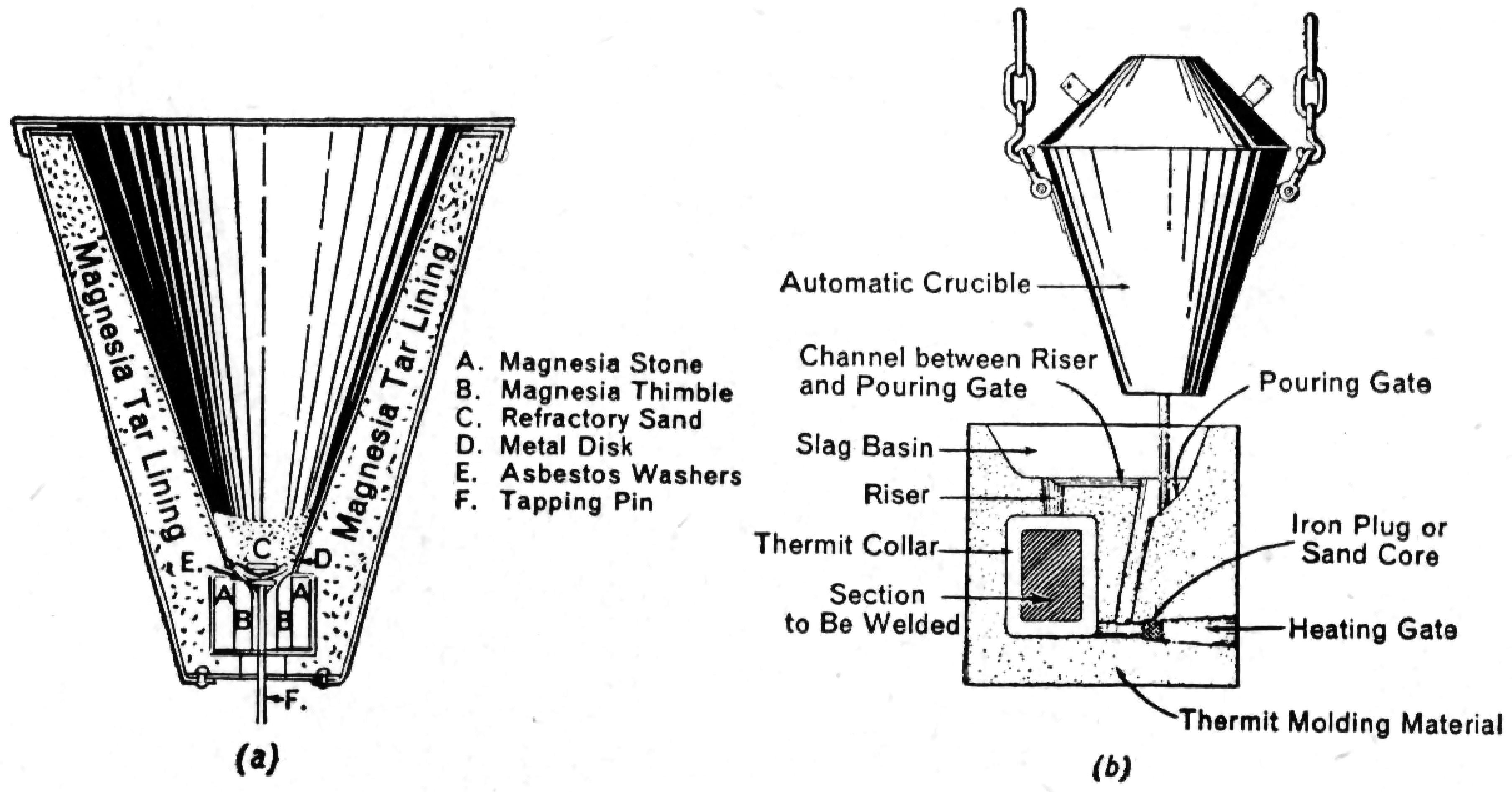

Magnesia Tar Lining
Magnesia Tar Lining
C
E.
D.
A
B
B
A
F.
A. Magnesia Stone
B. Magnesia Thimble
C. Refractory Sand
D. Metal Disk
E. Asbestos Washers
F. Tapping Pin
(a)
Automatic Crucible
Channel between Riser and Pouring Gate
Pouring Gate
Slag Basin
Riser
Thermit Collar
Iron Plug or Sand Core
Section to Be Welded
Heating Gate
Thermit Molding Material
(b)

FIG. 12–1: At (*a*), thermit crucible; and at (*b*), crucible and thermit mold.

12–7. Gas Welding. The two prevailing combustible gases utilized for welding are acetylene (C_2H_2) and hydrogen (H_2), of which the former is preponderantly the more commonly used. The oxygen-hydrogen process is well adapted to the welding of low melting metals—such as lead, aluminum, tin, or zinc base white metals—because of a lower flame temperature.

The oxyacetylene process of welding preceded by several years any widespread use of other fusion methods and today ranks second in use only to the electric arc process.

12–8. Acetylene. Acetylene is a hydro-carbon gas, consisting of 92.3 per cent carbon and 7.70 per cent hydrogen by weight, corresponding to symbol C_2H_2. It is a colorless combustible gas and is one of the products of the decomposition of calcium carbide, CaC_2 in water. It is produced in an acetylene generator, shown in Fig. 12–2, according to equation:

$$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$$

Calcium carbide + water → acetylene + hydrated lime

Calcium carbide is a stony, grayish substance obtained by sintering about 66 per cent limestone and 33 per cent coke in an electric arc furnace.

During its production, acetylene exhibits strong endothermic characteristics by storing up a large quantity of latent energy which is released in the form of heat during combustion. This property, peculiar to only few known gases, enables acetylene, when burned with oxygen, to produce the hottest gas flame known. Since it is an endothermic gas compound, precautions must be taken to avoid its dissociation into its components by subjecting it in an undissolved state to either heat, shock, or pressure in excess of 15 psi. However, in order that it may conveniently, economically, and safely be made available to consumers at higher pressures, the seamless acetylene tanks contain porous substances—such as asbestos, balsa wood, infusorial earth, charcoal, or cement—which divide the interior of the tank into minute cells, as shown in Fig. 12–3 at (*a*). The cylinder is then filled to 40 per cent of its capacity with acetone (C_3H_6O), a liquid chemical which dissolves about 24 volumes of acetylene per unit volume

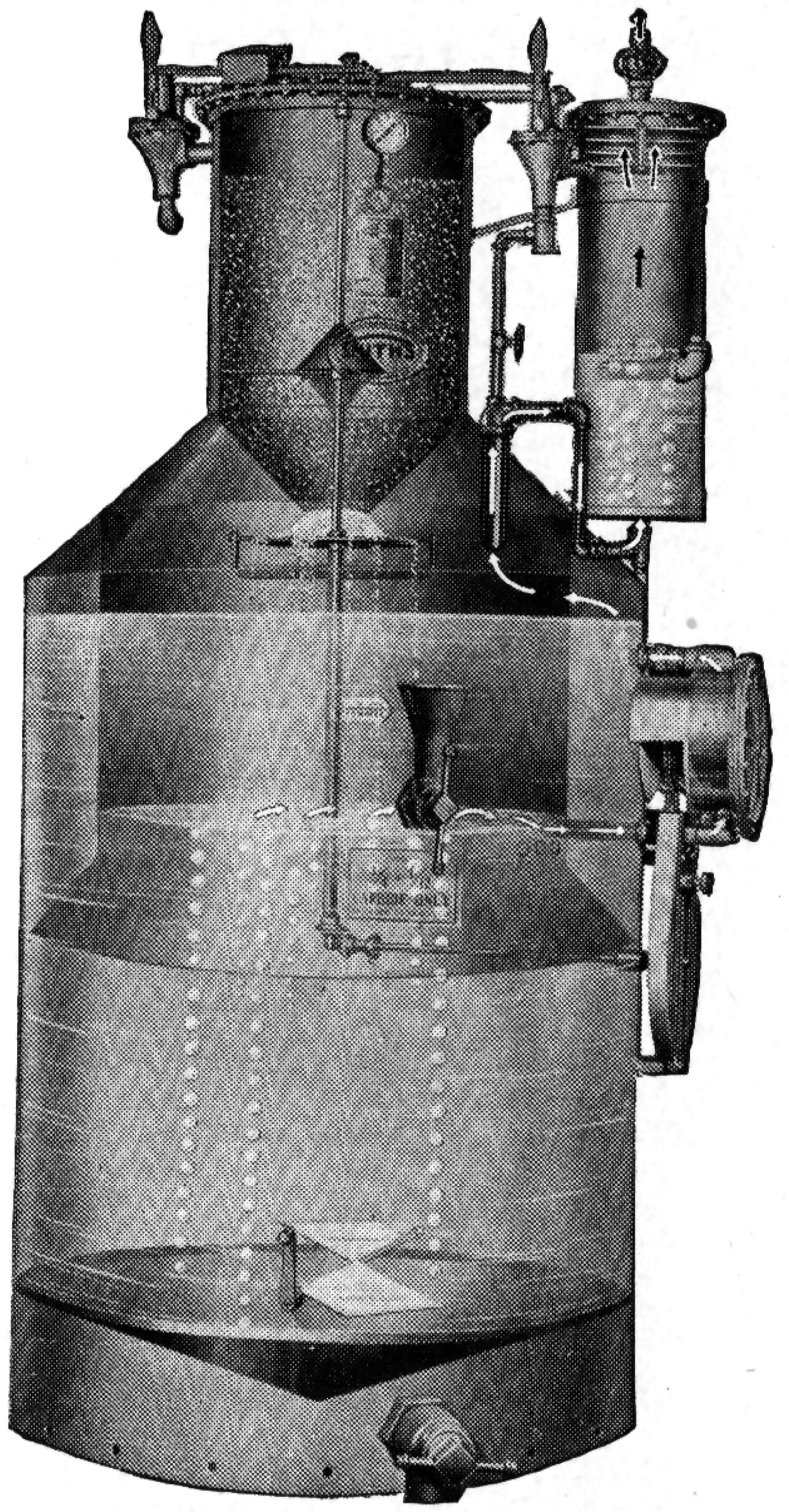


FIG. 12–2: Acetylene generator.

at atmospheric pressure. Furthermore, this property increases directly as the pressure so that at 45 lb about 75 volumes are soluble, and at 250 lb about 420 volumes. Thus, the cylinder is rendered perfectly safe for transportation and use.

A commercial size tank of acetylene contains approximately 275 cu ft of gas at 250 lb pressure and 70F.

12–9. Oxygen. Oxygen is produced commercially by the liquefaction of atmospheric air. Its production involves cooling and compressing to a temperature of about −320F, at which temperature it is converted to liquid oxygen and nitrogen. When these cold liquids are permitted to warm up gradually, the nitrogen begins to boil while the oxygen is still in the liquid state. When the temperature reaches −296F, the oxygen begins to boil, and the gas is collected, later to be compressed into seamless steel tanks, shown in Fig. 12–3 at (*b*), at a pressure of over 2,000 psi at 70F.

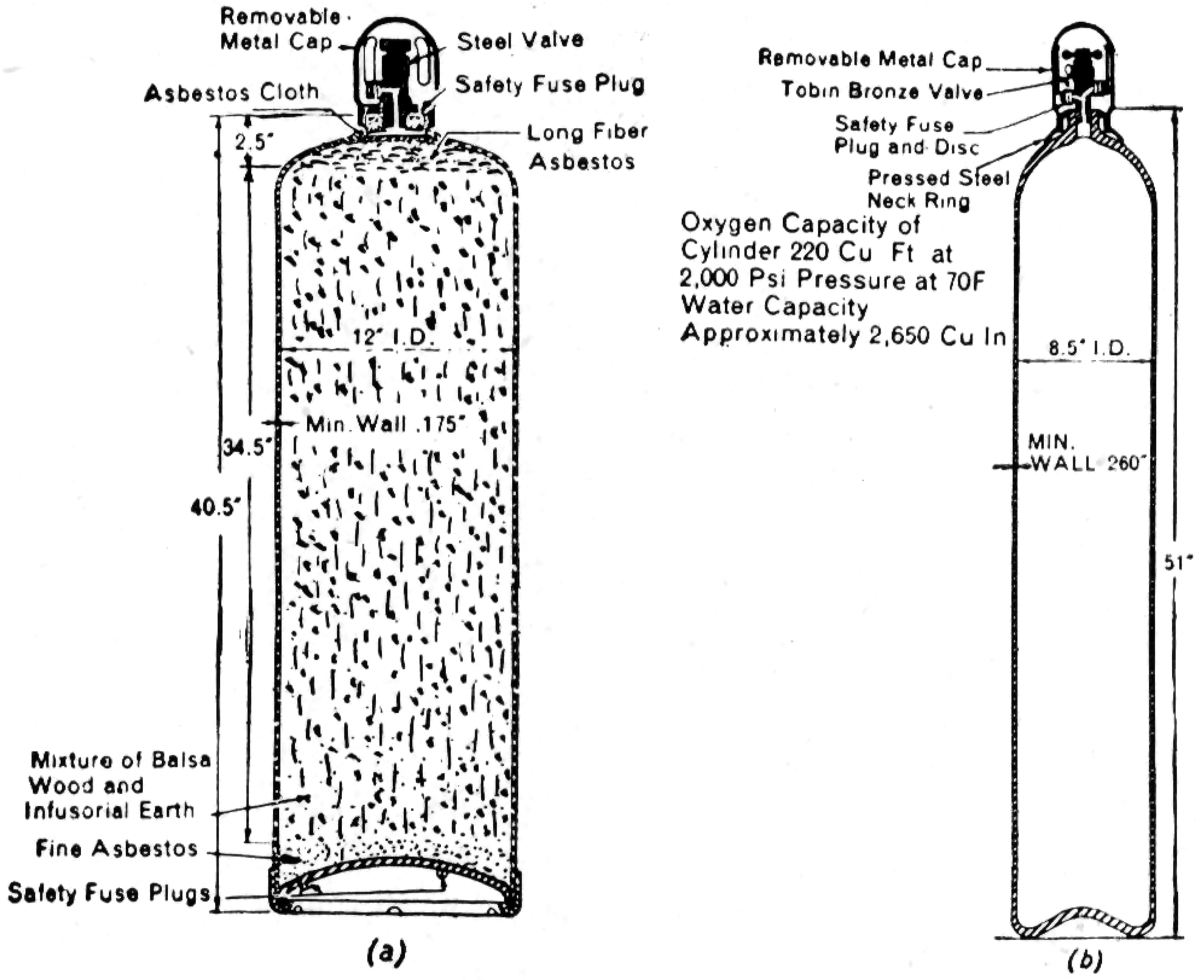

Removable Metal Cap
Steel Valve
Safety Fuse Plug
Asbestos Cloth
Long Fiber Asbestos
2.5"
12" I.D.
Min. Wall .175"
34.5"
40.5"
Mixture of Balsa Wood and Infusorial Earth
Fine Asbestos
Safety Fuse Plugs
(a)
Removable Metal Cap
Tobin Bronze Valve
Safety Fuse Plug and Disc
Pressed Steel Neck Ring
Oxygen Capacity of Cylinder 220 Cu Ft at 2,000 Psi Pressure at 70F Water Capacity Approximately 2,650 Cu In
8.5" I.D.
MIN. WALL .260"
51"
(b)

FIG. 12–3. At (*a*), seamless acetylene tank, showing porous filler material; and at (*b*), seamless oxygen container.

12–10. Regulators and Gauges. Acetylene and oxygen tanks must be equipped with regulators or reducing valves to control and maintain the pressure of the gases at values required for the various welding jobs. These pressures are obtained by the adjustment of a crossbar handle. Attached to each regulator are two gauges which indicate the tank pressure and the working pressure, as well as the number of cubic feet of gas in the tank. Welding torches are connected to the gas tanks through the regulators by means of two strong, but light and flexible, rubber hoses—a green colored one for the oxygen, and a red one for the acetylene—which are equipped with right- and left-hand couplings, respectively.

12–11. Torches. Welding blowtorches are classified according to the relative size of the ports or orifices through which the gases pass. The basic design of torches provides for delivery of the gases in equal volumes to the extreme outside end of the tip where they burn.

Instructions accompanying equipment should be followed to obtain correct gas pressures for tips of different size and for fullest efficiency from the torch.

The body or handle of the torch is made of brass, bronze, or monel metal; and the tips are made of forged copper, in order to conduct heat away and to avoid overheating the end at which the gases burn. These tips are easily removable, and several sizes comprise a set from which the appropriate one can be selected for welding metals of various thicknesses.

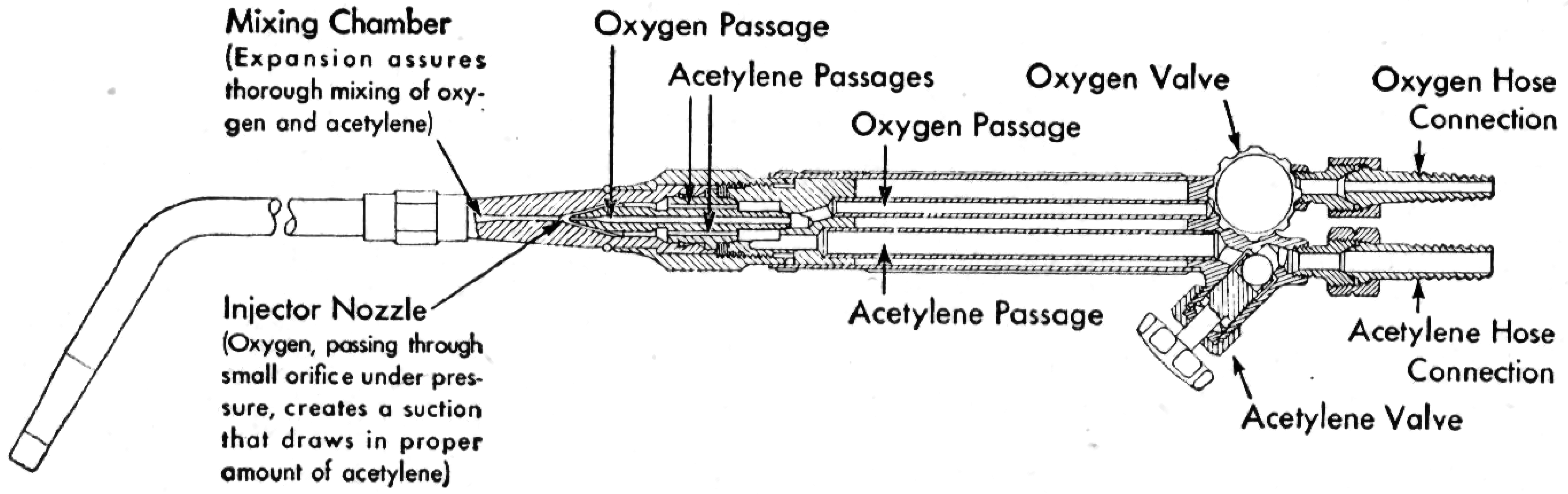

Mixing Chamber (Expansion assures thorough mixing of oxygen and acetylene)
Oxygen Passage
Acetylene Passages
Oxygen Valve
Oxygen Hose Connection
Oxygen Passage
Injector Nozzle (Oxygen, passing through small orifice under pressure, creates a suction that draws in proper amount of acetylene)
Acetylene Passage
Acetylene Hose Connection
Acetylene Valve

FIG. 12–4. Cross-section of injector-principle welding blowpipe. (Courtesy of The Linde Air Products Company.)

Torches consist essentially of two tubes through which the gases pass until they unite and become intimately mixed in a mixing chamber, as shown in Fig. 12–4. Two needle valves on the torch handle permit easy adjustment and regulation of the flame.

12–12. Chemistry. The complete combustion of acetylene into carbon dioxide (CO_2) and water (H_2O) requires a ratio of 2½ volumes of oxygen to one of acetylene and may be shown by the equation: $2C_2H_2 + 5O_2 \rightarrow 4CO_2 + 2H_2O$. In a welding blowtorch, however, this reaction occurs in two stages as shown in Fig. 12–5. The maximum flame temperature is obtained when the acetylene is burned in a deficiency of oxygen according to the equation: $2C_2H_2 + 2O_2 \rightarrow 4CO + 2H_2$. Since both carbon monoxide and hydrogen are combustible gases, a further reaction takes place in the outer parts of the flame when the carbon monoxide (CO) and the hydrogen (H_2) combine with additional oxygen from the surrounding atmosphere, according to the equation: $4CO + 2O_2 \rightarrow 4CO_2$; $2H_2 + O_2 \rightarrow 2H_2O$, with the resultant decreasing temperature as shown.

12–13. Uses of Oxyacetylene Blowtorches. The principal function of the oxyacetylene torch is to weld metals. The concentrated application of the flame produces fluidity in the metal and the welding rod, or filler metal, which are brought together to form a weld by fusion. Although the most desirable welding conditions prevail when the metals are in a flat or horizontal position, oxyacetylene welding may also be accomplished in the vertical or overhead positions. The various positions are shown in Fig. 12–6. In welding plates in the flat positions, operators employ techniques known as backhand welding and forehand welding. The backhand method is the more efficient and most commonly used, although much depends on habits formed. Fig. 12–7 shows a complete assembly for oxyacetylene welding.

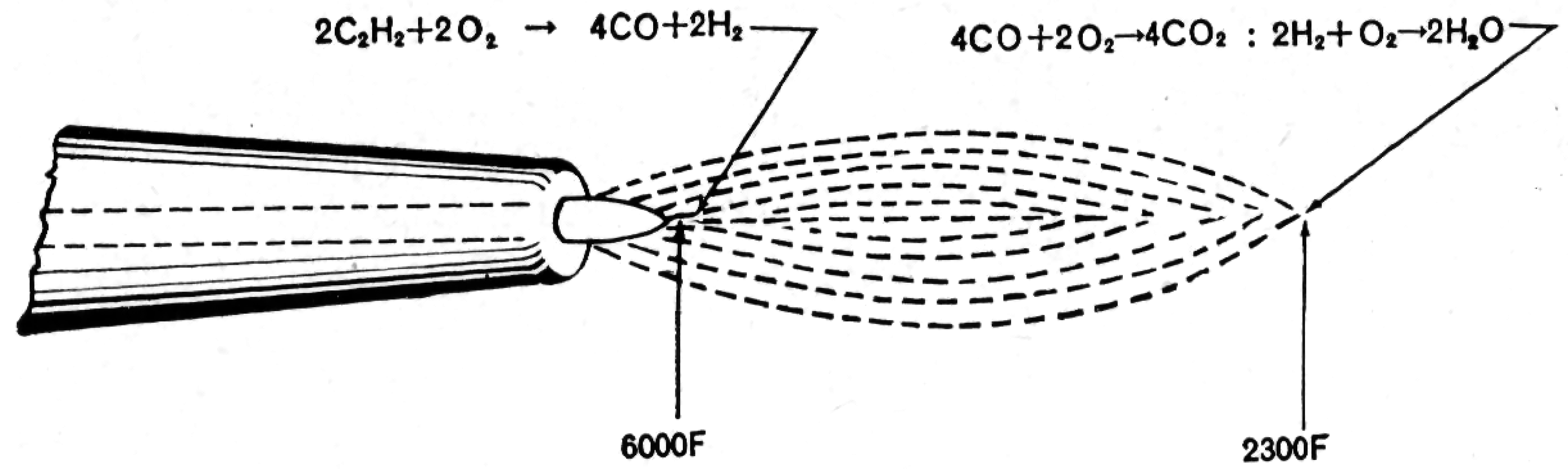

$2C_2H_2+2O_2 \rightarrow 4CO+2H_2$
$4CO+2O_2 \rightarrow 4CO_2 : 2H_2+O_2 \rightarrow 2H_2O$
6000F
2300F

FIG. 12–5. Reaction products of the combustion of acetylene and oxygen in a welding blowtorch.

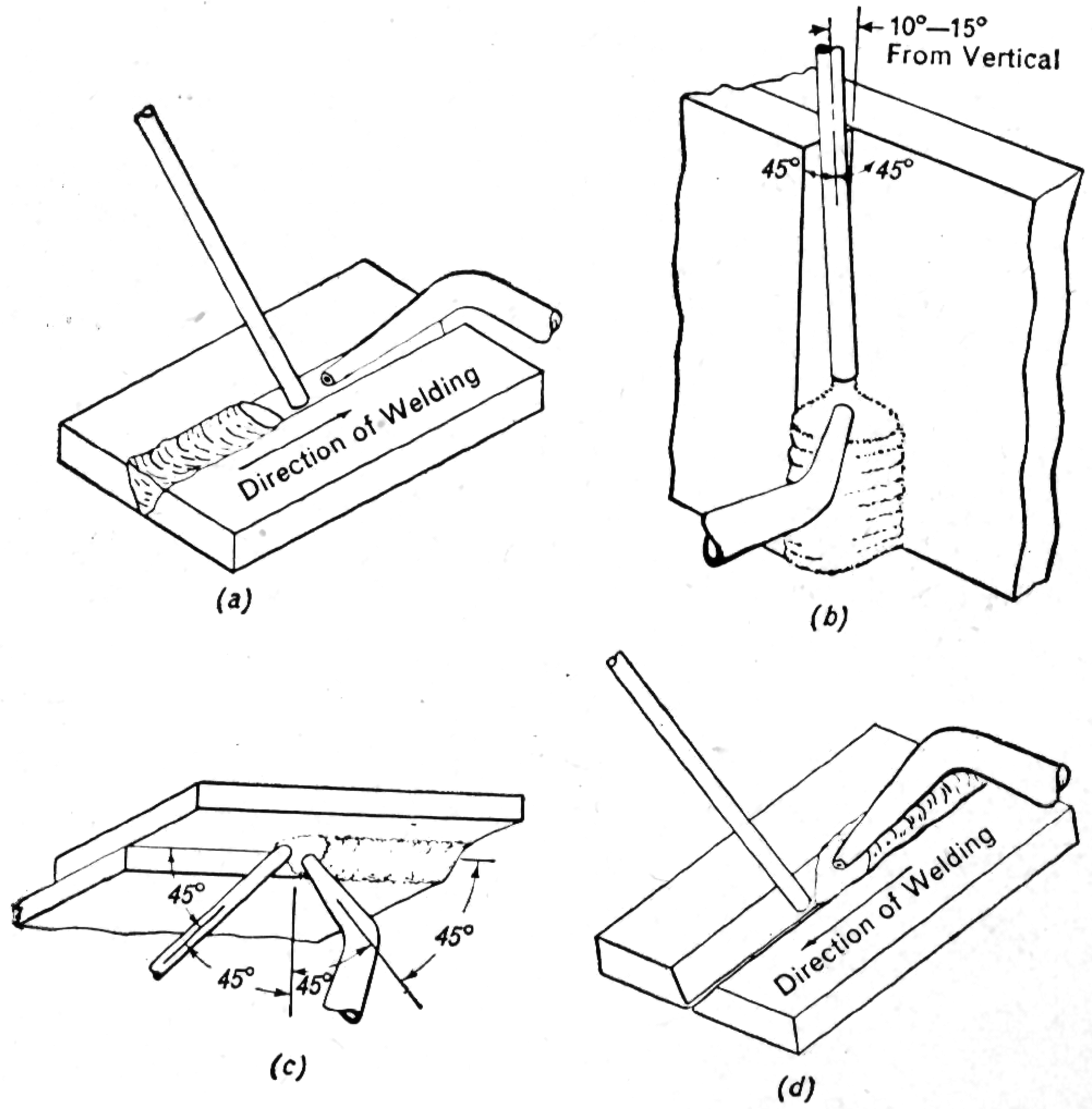

10°—15° From Vertical
45°
45°
Direction of Welding
(a)
(b)
45°
45°
45°
45°
(c)
Direction of Welding
(d)

FIG. 12–6. Welding positions: at (*a*), backhand; at (*b*), vertical; at (*c*), overhead; and at (*d*), forehand.

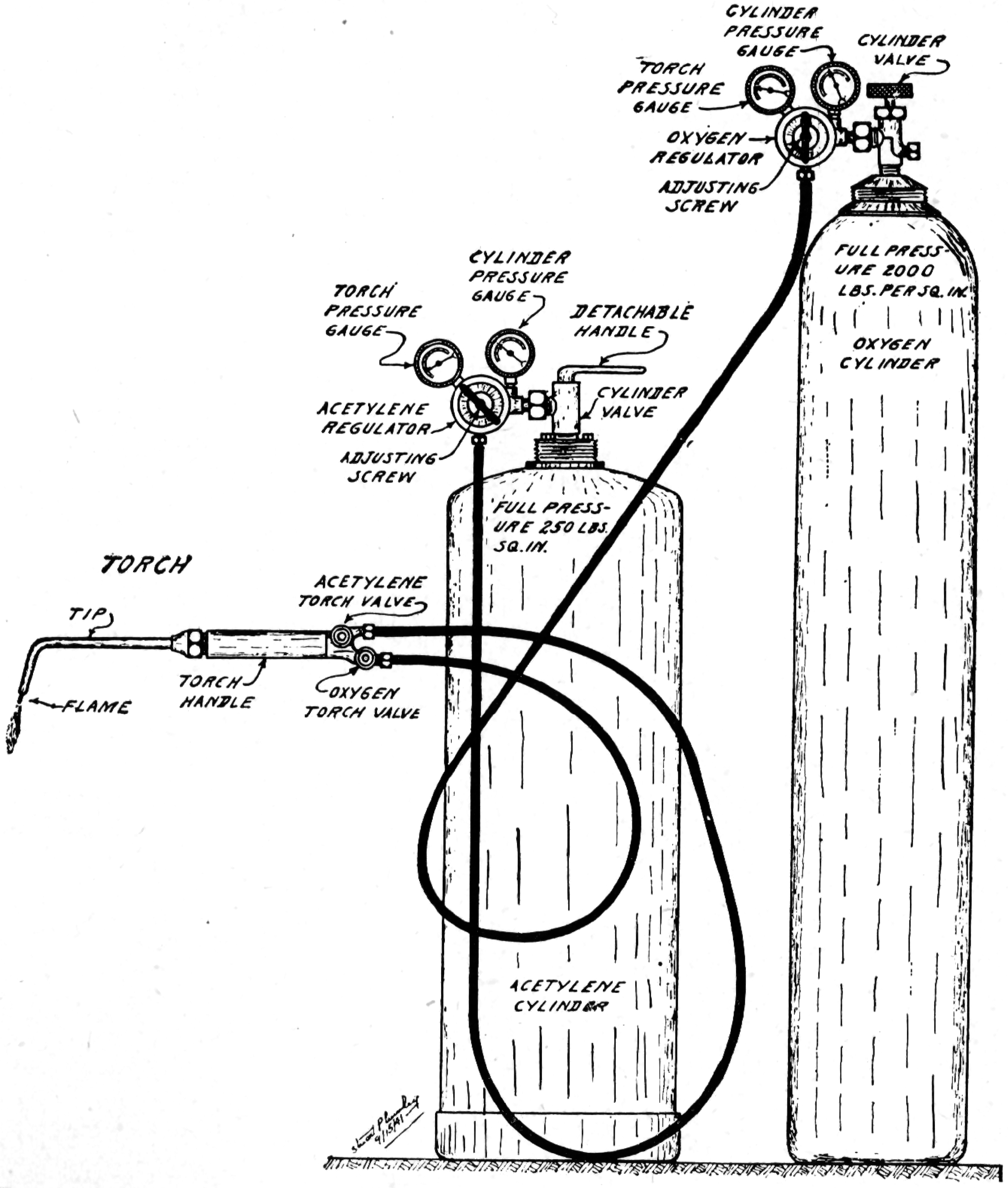

CYLINDER PRESSURE GAUGE
CYLINDER VALVE
TORCH PRESSURE GAUGE
OXYGEN REGULATOR
ADJUSTING SCREW
FULL PRESSURE 2000 LBS. PER SQ. IN.
OXYGEN CYLINDER
TORCH PRESSURE GAUGE
CYLINDER PRESSURE GAUGE
DETACHABLE HANDLE
CYLINDER VALVE
ACETYLENE REGULATOR
ADJUSTING SCREW
FULL PRESSURE 250 LBS. SQ. IN.
TORCH
TIP
ACETYLENE TORCH VALVE
FLAME
TORCH HANDLE
OXYGEN TORCH VALVE
ACETYLENE CYLINDER

FIG. 12–7. Sketch showing an assembled view of two cylinders, two regulators, hose lines, and torch.

Generally the oxyacetylene process is best adapted to the welding of the thinner metals—sheets, pipes, tubings, and nonferrous materials, such as aluminum and copper. In numerous instances it is advantageously used in preference to other processes for welding gray cast-iron, particularly where subsequent machinability of the weld metal is desirable. It is also widely used for brazing or bronze welding.

The employment of the oxyacetylene torch for welding constitutes but a small part of its general versatility. Some of its many and varied uses can only be mentioned in a text of this kind, while some others demand discussion and study as integral parts of the welding process. The use of the oxyacetylene torch for welding is becoming of secondary importance to its use for flame-cutting ferrous metals preparatory to welding and to its use as a substitute method of producing parts previously made by machining or forging.

12–14. Flame-Cutting. When a ferrous base metal is heated to a bright red color (about 1500F) and a stream of oxygen of high purity under pressure is directed upon it through a nozzle or orifice, the metal reacts chemically with the oxygen to form an oxide of iron as shown by the equation: $3Fe + 2O_2 \rightarrow Fe_3O_4$ (magnetic oxide). If sufficient pressure is used, this oxide is blown out of a narrow cut or *kerf* directly in the path of the oxygen. When correct techniques are used, especially when the torch travel is mechanically controlled, the kerf consists of uniformly smooth parallel surfaces comparable to a roughly machined surface; and for many purposes these surfaces require no further machining.

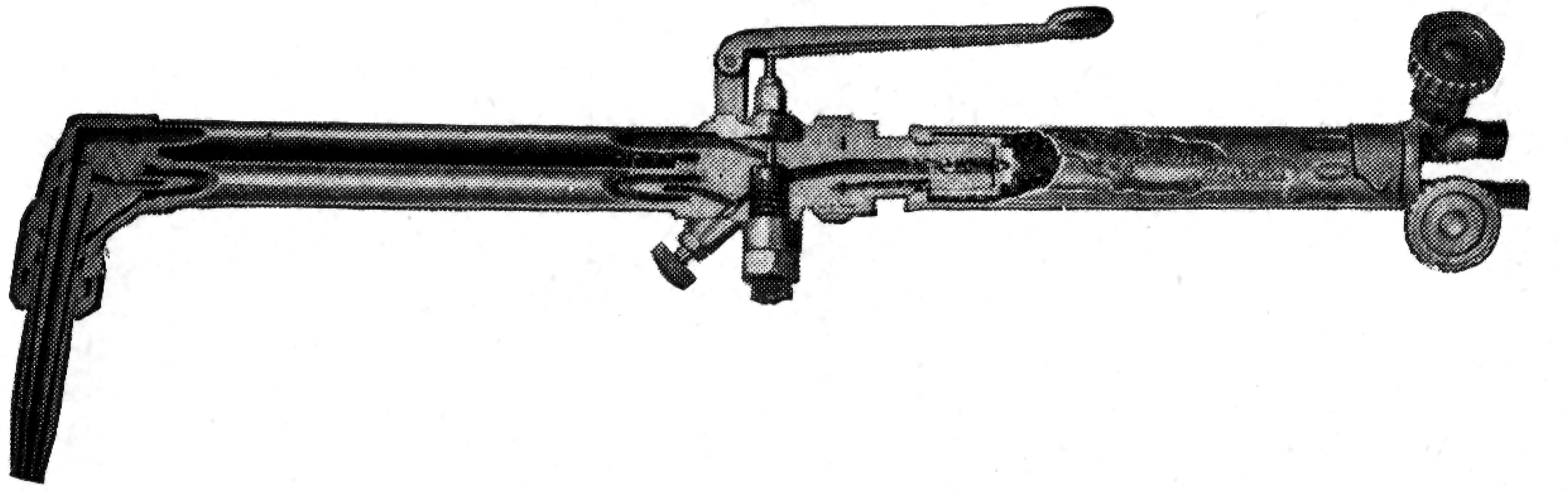


FIG. 12–8. Cutting torch.

The cutting torch shown in Fig. 12–8 is designed to provide for preheating the metal with the aid of a number of flames, comparable to the welding flame, which issue out of the tip through orifices surrounding a central, but usually larger orifice, through which the oxygen is directed upon the metal surface. When the metal is sufficiently preheated, the operator manipulates a trigger on the torch whereby the main oxygen stream is diverted into a port which leads it to the tip. To compensate for the loss of the heat of oxidation through conduction and radiation, the preheating flame is maintained during the cutting of commercial shapes. The operation of cutting may be carried out manually or mechanically, and combustible gases other than acetylene, particularly propane, may be used.

A variety of mechanically controlled gas-cutting machines produce flame-cut shapes of almost all description on thicknesses of steel up to

40 in. and operate after the manner of production machine tools. Attainable speeds and gas consumptions for manual and mechanical cutting of steels of various thicknesses are given in Tables 12–2 and 12–3.

TABLE 12–2

MANUAL CUTTING*

Plate Thickness (In.)	Cutting Speed (Ft/Hr)	Gas Consumption (Cu Ft/Hr)	
		Oxygen	Acetylene
1/4	95	50	14
1/2	85	90	18
1	55	146	24
2	31	206	28
4	25	372	35
12	9.5	840	40

*Attainable speeds at recommended adjustments for manual oxygen-cutting are summarized in this table.

TABLE 12–3

MECHANICAL CUTTING*

Plate Thickness (In.)	Cutting Speed (Ft/Hr)	Gas Consumption (Cu Ft/Hr)	
		Oxygen	Acetylene
1/4	110	70	15
1/2	92	104	18
1	66	166	21
2	47	245	27
6	27	500	40
12	16	925	55

*Average machine cutting speeds and gas consumptions are given in this table.

Many models of cutting machines are equipped with as many as 20 torches, all cutting simultaneously. The path traveled by the torches may be controlled by means of small strips of metal, known as templates, which are attached to plates and correspond to the shape of the desired product.

Factors which affect the quality and speed of cutting ferrous metals are: (1) purity of the oxygen, (2) size of preheating flame, (3) speed of travel, (4) thickness of metal, (5) precision required, (6) type of steel, (7) correct torch size, and (8) cleanliness of orifice.

12–15. Summary of Influence of Alloy Elements on Oxygen-Cutting.* Manganese steels of 14 per cent manganese and 1.5 per cent carbon are cut with difficulty and should be preheated for best results.

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*Crowe and Denning, *Welding Handbook* (1938 ed.).

Silicon in the range commonly found in steels has no effect. Transformer irons containing up to 4 per cent silicon may be cut. Silicon steels containing considerable amounts of carbon and manganese must be carefully preheated and postheated for best physical properties.

Chromium reacts with oxygen only when at very high pressure. Steels containing up to 5 per cent chromium are cut without much difficulty when the surface is clean. Higher chromium steels, such as 10 per cent chromium, require special technique, and the cuts are rough. In general a slight excess of acetylene in the preheating flame is desirable in cutting high-chromium steels.

Steels with nickel content up to 20 per cent or 30 per cent, if the carbon is not too high, may be cut. Up to 7 per cent nickel cuts are very satisfactory.

Molybdenum reacts on cutting just as chromium does. Aircraft quality chrome-molybdenum steel offers no difficulty but should be preheated to prevent hard edge.

Alloys containing up to 12 or 14 per cent tungsten may be cut readily, but higher tungsten makes cutting difficult with a limit of about 20 per cent.

In amounts up to about 2 per cent, copper has no apparent effect.

The effect of aluminum, unless present in amounts of about 10 per cent, is inappreciable. Neither phosphorus nor sulphur in amounts allowable in commercial steels presents any obstacle to cutting.

Vanadium in small amounts may improve rather than interfere with cutting.

12–16. Cutting of Nonferrous Metals.* While any nonferrous metal may be severed by melting, its oxidation, if a factor at all, is relatively unimportant. The four main reasons advanced for the failure of the oxygen-cutting process when applied to nonferrous metals are: (1) the metal has a low or negative heat of oxidation, (2) intergranular penetration of the oxide into the metal does not occur, (3) the melting point of the oxide is higher than the melting point of the metal, and (4) the ignition temperature is higher than the melting point of the metal.

12–17. Stack Cutting. Where large numbers of identical parts are required, relatively thin plates may be stacked, one on top of the other, to a thickness equal to the capacity of the torch. When held tightly together with clamps or weld beads, the pile may be cut as a solid piece. The limitations, aside from the maximum thickness, are (1) quality of cut desired, (2) type of steel, and (3) dimensional tolerance.

12-18. Metallurgical Effect of Cutting. The knowledge of the influence of the various constituents on the hardenability of steel quenched from a red heat has led to extensive studies of the metallurgical effect of the cutting operation on the structure adjacent to the cut edge of metals. These have resulted in the development of procedures which can be applied successfully to the cutting of practically all commercially useful ferrous metals.

The degree to which steel hardens is a function of chemical analysis (principally the carbon), the temperature from which it is cooled, and the rapidity at which heat is abstracted. During cutting, the metal immediately adjacent to the cut edge is rapidly heated and subsequently rapidly cooled by the conduction of heat through the cold plate and by radiation. Therefore, if the amount of carbon is sufficient or certain alloying elements are present, a thin layer of hard unmachinable metal on the cut surface is produced which, because of the resultant lower ductility, may cause minute cracks as a consequence of the cooling stresses, leading to failure of the part. To obtain most economical use of the gases and to reduce the cooling rate, higher carbon and alloy steels are heated from 500 to 1000F preceding the cutting. When cold-cutting has produced undesirable hardness, postheating or annealing may be employed. Postheating, however, will not eliminate cracks which have already developed.

In the commonly welded low-carbon steels, the cut surfaces are not injured by the cutting operation, and preheating of plates of higher carbon and alloy steels makes cutting wholly practicable.

12-19. Oxyacetylene Pressure Welding. One of the welding processes most recently developed is that of welding ferrous and some nonferrous metals by the proper correlation of pressure and temperature.

The process, also called solid phase welding, provides means of effecting a strong bond between metals by atomic diffusion or coalescence of grains across weld surface at subfusion temperatures.

The ends of the parts to be welded are machined to a fairly smooth, clean surface and are held in intimate contact under pressure throughout the heating phase and while the welding is being executed.

For welding plain carbon and alloy steels the weld zone is heated by means of a multiple tip oxyacetylene heating head to a uniform temperature from 2192 to 2282F. Nonferrous metals are heated to lower temperatures corresponding to their lower melting points. Simultaneously with the heating phase, pressure ranging from 1,500 to 4,500 psi (depending on the metals) is applied to the already closely abutting faces by means of a hydraulically or mechanically operated clamping device and continued until a predetermined amount of shortening or upsetting of the parts has occurred. When the weld is completed, it is allowed to cool normally or, when high-carbon and alloy steels are welded and the weld metal requires normalizing for grain refinement, it is reheated to the proper temperature.

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*Spraragen and Claussen, "A Review of the Literature to July 1938," *Welding Journal* (Sept. 1938, ed.).

The process is used for welding pipe lines for oil and gas, railroad rails, and gas containers. Some hundreds of miles of pipe lines with pipe diameters ranging from 2 to 24 in. have been welded and laid by this process. Welding time of 1 to 1½ min is claimed per joint in pipe of all diameters.

The principal factors in the production of quality welds are (1) preparation of abutting ends, (2) correct temperature, (3) the amount and duration of the pressure.

The advantages claimed for the process over other competing processes are (1) it is adaptable to a wide range of both ferrous and nonferrous alloys, (2) welds of good quality are possible in the relatively high-strength low-alloy steels and high-C steels, (3) weld cracking tendencies are reduced by the slow and uniform cooling rate, (4) dissimilar metals such as carbon and stainless alloys can be satisfactorily welded together, (5) it is almost completely mechanized and is adaptable for both shop and field erection, and (6) less time is consumed than with other processes on comparable materials.

Some of the metals other than steels which have been pressure-welded include Nichrome (80 per cent Ni, 20 per cent Cr), Monel (67 per cent Ni, 33 per cent Cr), Everdur (95.5 per cent Cu, 3.5 per cent Si, 1 per cent Mn), Yellowbrass (70 per cent Cu, 30 per cent Zn), Tobin bronze (60 per cent Cu, 39 per cent Zn, 1 per cent Sn), and some of the aluminum-iron bronzes (82–90 per cent Cu, 4–13.5 per cent Al, 4.5 per cent Fe).

12–20. Submerged Arc Process. The importance of the recently developed single-pass submerged arc welding processes was much accentuated during World War II by their phenomenal contribution to the increased production of such war equipment as ships, guns, tanks, and railroad cars, as well as to other industrial uses. One process known as "Unionmelt" is widely used for welding low-carbon and alloy steels in thicknesses ranging from 3/16 to 4 in. at rates incomparably greater than those possible by any other process. Welding rates are shown in Table 12–4.

The distinguishing feature of the Unionmelt process is its utilization of a finely granulated mineral; see Fig. 12–9. When poured into the weld groove ahead of the electrode wire, this material becomes fused as the arc is struck and completely shields the arc underneath. The high resistance of the mineral to electrical conduction when in a fused condition provides large quantities of heat for the fusion of a relatively large volume of base metal and filler rod. Since the fusion takes place below the surface of the molten mineral, the metal is shielded against oxidation by atmospheric gases, and the fused mineral rises to the surface of the metal where it solidifies as a slag, which is easily removed on cooling. The unfused portion of the mineral remains unchanged and is returned to the supply source by a vacuum system.

TABLE 12–4

SUMMARY OF VARIOUS FACTORS FOR SUBMERGED ARC WELDING*

THICKNESS (IN.) T.	VEE (DEG.) V.	NOSE (IN.) N.	AMPS	VOLTS	SPEED, (IN./MIN)	WELDING ROD Diam. (In.)	WELDING ROD Lb/ft
¼	60	⅛	725–828	29–32	28–31	3/16	0.14–0.23
⅜	60	⅛	900–1,000	32–36	24–27	¼	0.28–0.35
½	60	3/16	1,075–1,175	34–37	20–23	¼	0.38–0.45
⅝	45	3/16	1,150–1,250	35–38	16–19	¼	0.50–0.58
¾	45	3/16	1,200–1,300	36–39	13–14	¼	0.60–0.75
⅞	40	⅛	1,375–1,500	38–40	11–13	5/16	0.80–0.95
1	35	⅛	1,500–1,600	39–41	10–12	5/16	0.90–1.10
1⅛	30	⅛	1,575–1,650	39–41	9–10	5/16	1.00–1.25
1½	30	⅛	1,900–2,000	40–43	7–8	⅜	1.85–2.00

* *Welding Handbook* (1942 ed.).

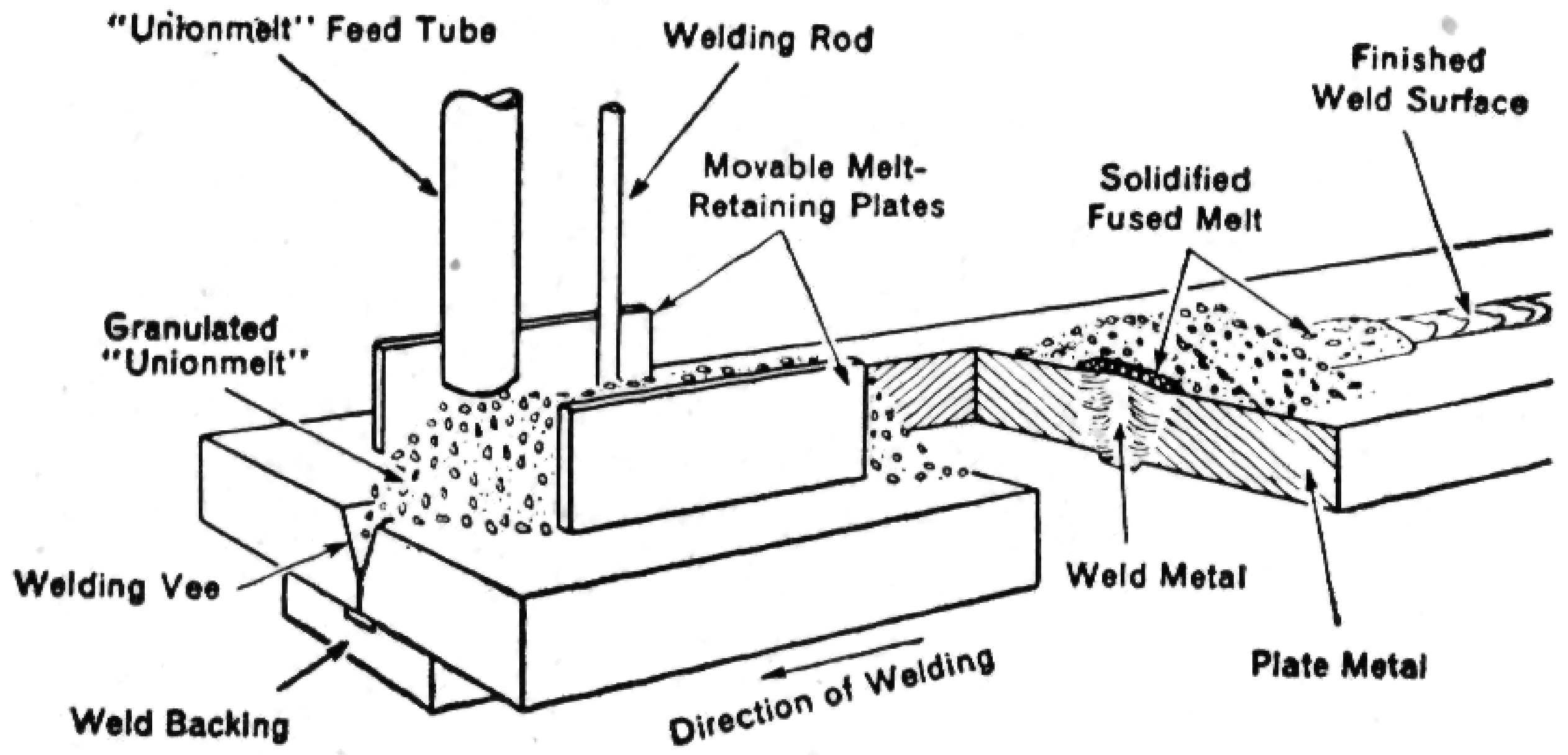


FIG. 12–9. Various elements involved in the making of a submerged arc "Unionmelt" butt weld. (Courtesy of The Linde Air Products Company.)

Although fundamentally an arc welding process, submerged welding must not be confused with conventional manual and automatic arc welding processes. Like arc welding, the process operates on either alternating or direct electric current and employs a voltage across the arc ranging from 20 to 55 v. The amperages, however, are considerably higher than those used in manual arc welding. The capacity of the largest available equipment ranges up to 4,000 amp.

Plate preparations for submerged welding, such as beveling the edges and preparing and cleaning the surface, are fundamentally like those used in welding similar thicknesses of metal by other processes. The fusion of a large volume of metal by the intense heat developed, however, makes possible a much smaller included angle for a Vee butt joint than when either the electric arc or the oxyacetylene process is used.

The electrode or filler metal consists of a drawn wire having neither covering nor coating. This is automatically fed into the joint by an electrically controlled welding head from an overhead coil, mounted on either a stationary or movable support. The diameter and the composition of the electrode vary as required for welding steels of different thicknesses and analyses. In addition the welding head performs the dual functions of progressively depositing the material in the joint and of transmitting the welding current to the electrode.

The almost completely automatic features of submerged arc welding largely reduce dependence on operator's skill for the consistent production of quality welds and therefore materially shorten the normal operator training period. After the welding conditions have been determined, the arc is started by the insertion below the mineral surface of a small wad of steel wool placed in contact with the electrode. Immediately upon switching on the current, heat generated at the lower tip of the electrode fuses the mineral, the welding rod, and the base metal through the medium of the molten mineral, without their actual contact. After the welding is thus started, no further attention by the operator is required until the weld is completed.

In addition to advantages resulting from no particular demand for dexterity, other advantages of the process are: (1) welds are made in one or two passes, thus reducing possible warpage and distortion; (2) higher production rates than with any other process are available; (3) quality welds can be consistently produced; (4) the requirements of the various welding codes which prescribe the strength, ductility, and soundness are adequately met; (5) no helmet, goggles, respirators, or ventilating systems are required for the operator since the entire reaction takes place underneath the surface of the slag and no gases are liberated; and (6) certain alloy steels, normally difficult to weld without a preheat by other processes, are reported successfully welded without preliminary heating by this process.

The necessity for controlling a relatively large pool of molten metal and slag restricts the use of the Unionmelt process to welding in an approximately flat or horizontal position. Circumferential seams in cylindrical vessels or drums are made by rotating the vessel as required by the welding rate, so that the electrode is nearly perpendicular to the horizontal weld surface. Macrostructures of welds are shown in Figs. 12–10A and 12–10B.

12–21. Electric Arc Welding. The basic principle involved in electric arc welding is that current continues to flow in the form of an arc as a result of the ionization of gases, which act as carriers of the current across a gap between two electrodes in momentary contact. Like other forms of energy, electricity must complete its cycle before it can be

utilized to produce work. Electric current for arc welding is derived from various types of mechanically operated d-c generators or from variable voltage transformers supplying alternating current. Rectified a-c to d-c and electronic welding sets are also being used. Generators are of the single or multiple operator types, while the transformers are more generally single operator units.

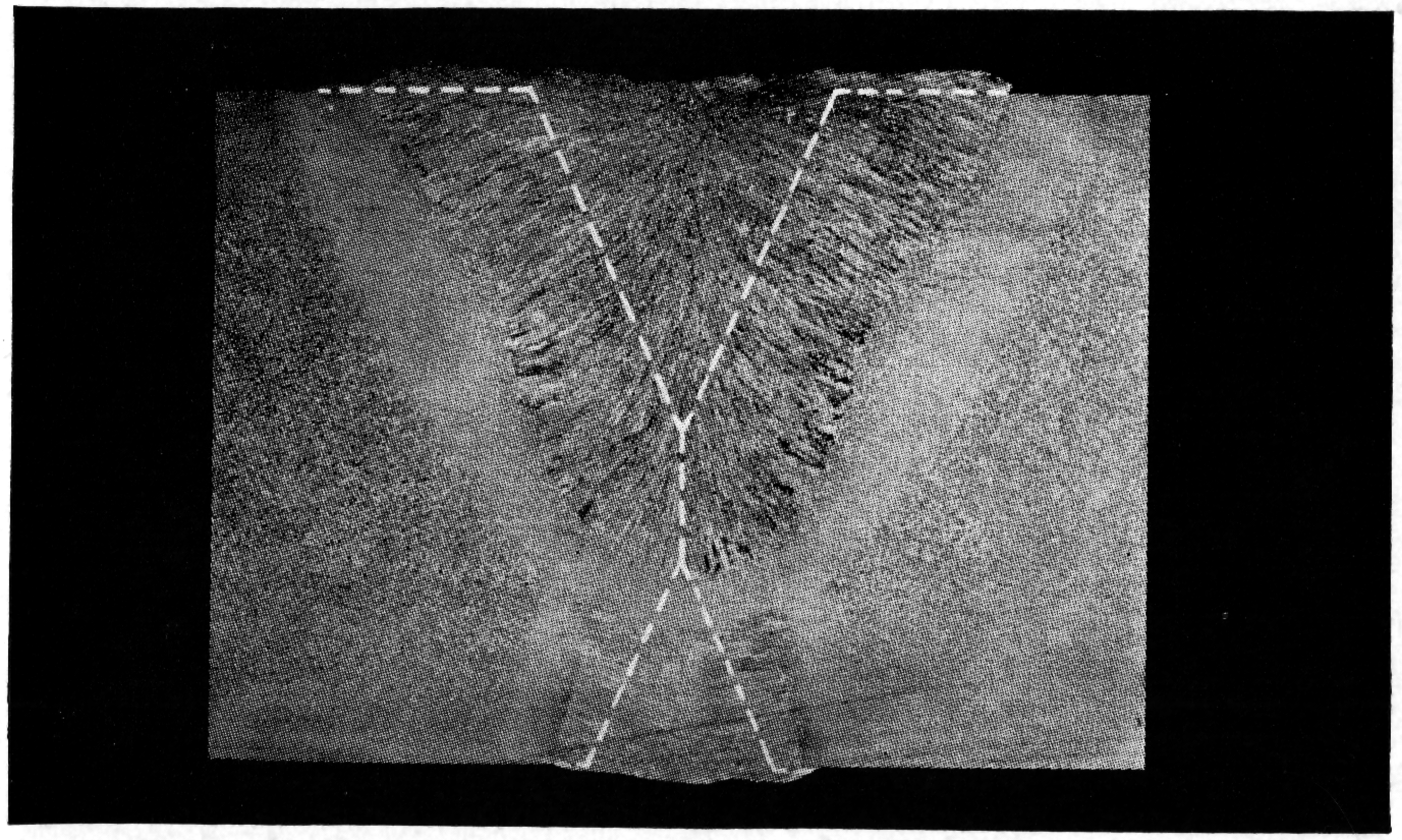


FIG. 12–10A. Two-pass submerged arc butt weld in 3½-in. steel plate. Note dendritic structure of weld metal and the heat-affected area adjacent to fusion zone. (Courtesy of The Linde Air Products Company.)

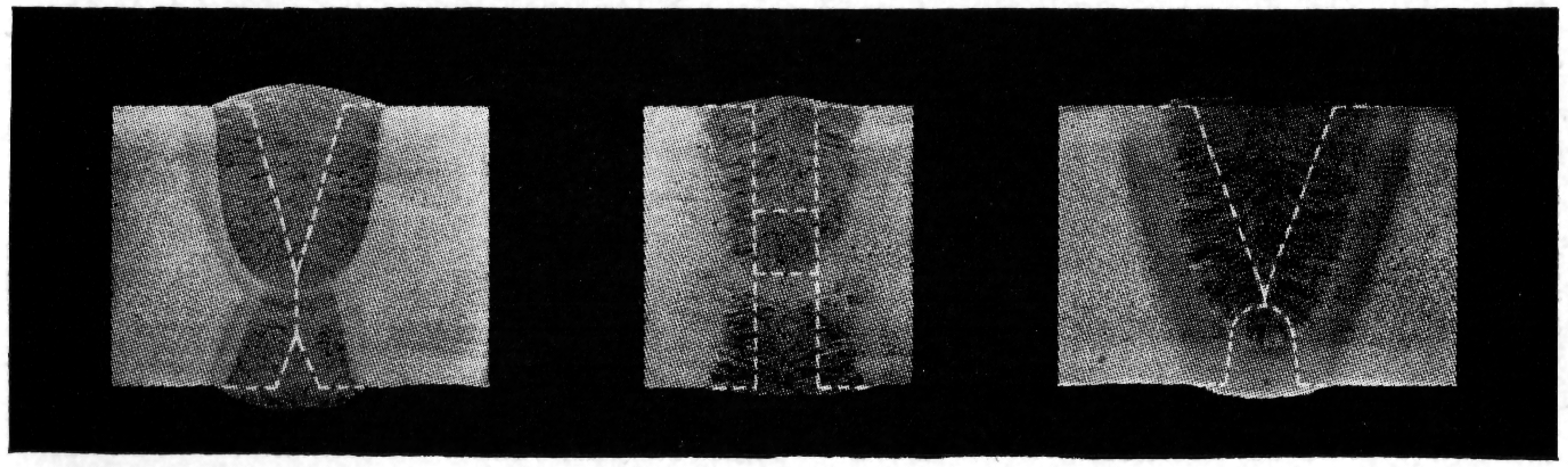


FIG. 12–10B. Types of plate edge preparation for submerged arc welds. (Courtesy of The Linde Air Products Company.)

Both types of electric current have distinctive welding advantages, although at present, the much larger share of arc welding is done with direct current.

When direct current is used, the metal to be welded constitutes one terminal of the electric circuit and a relatively smaller steel wire, called an electrode, constitutes the other. Under certain circumstances, determined principally by the characteristics of the electrode, the polarity of the two terminals may be alternated. Therefore, to obtain the best results, either the manufacturers' recommendations should be followed or the correct polarity should be determined by noting the elapsed time in burning off or melting a definite length of the electrodes, attaching first as one terminal and then the other and selecting the one which gives the better welding conditions. Usually a bare or lightly coated electrode is attached as the cathode or negative terminal of a d-c electric circuit, while the base plate is the positive terminal or anode. By this arrangement, the heat generated in the plate, which as a rule is larger than the electrode, is considerably greater than that at the cathode. This circuit is known as straight polarity.

During the past decade, the use of bare electrodes has been superseded by *coated* electrodes or the shielded arc process for manual construction welding, for various reasons pointed out later.

12–22. Current Values. Current requirements for manual arc welding are dictated by several factors, among which are the thickness of plate being welded, the size of electrode, the type of electrode, the specific properties of base plate, the position in which the weld is made, the skill of the operator, the type of joint, the quality of weld required, the fitup of joint, etc. All of these variable conditions are determining factors in the final selection. In general, the current ranges from 50 to 600 amp for manual welding and up to 3,000 amp for some automatic processes. As a rule, lower current is used for welding plates of comparable thickness in a vertical or overhead position than in the flat or horizontal position. For sounder welds and increased production, weldments are fixed in a jig or *positioner*, shown in Fig. 12–11, which provides for maximum horizontal or downhand welding. Generally, lower residual stresses in welded units result from the proper use of larger diameter electrodes and higher currents in preference to smaller electrodes and lower currents. Metals of low thermal coefficients require lower welding currents than do those of comparable thickness but of different specific properties.

The voltage across the arc varies directly as the length of the arc, and, for satisfactory quality welding with correct speed and economy, the length of the arc should remain constant and as short as is consistent with continuous and uninterrupted welding. A long arc results in reduced penetration of the plate, loss of metal by splattering, lower ductility, and greater porosity of weld metals. The average voltage across the arc varies between 20 and 25 v for bare and lightly coated electrodes and from 20 to over 40 v for heavily coated electrodes. In general, the length of the arc is equal to the diameter of the electrode, or approximately 3/32 in. for a 1/16-in. electrode or 1/4 to 3/8 in. for a 3/8-in. electrode. The open circuit or striking voltage, however, may range from less than 50 to 75 v.

The proper relation of current and voltage is obtained by advancing the electrode along the seam and by maintaining a constant arc length.

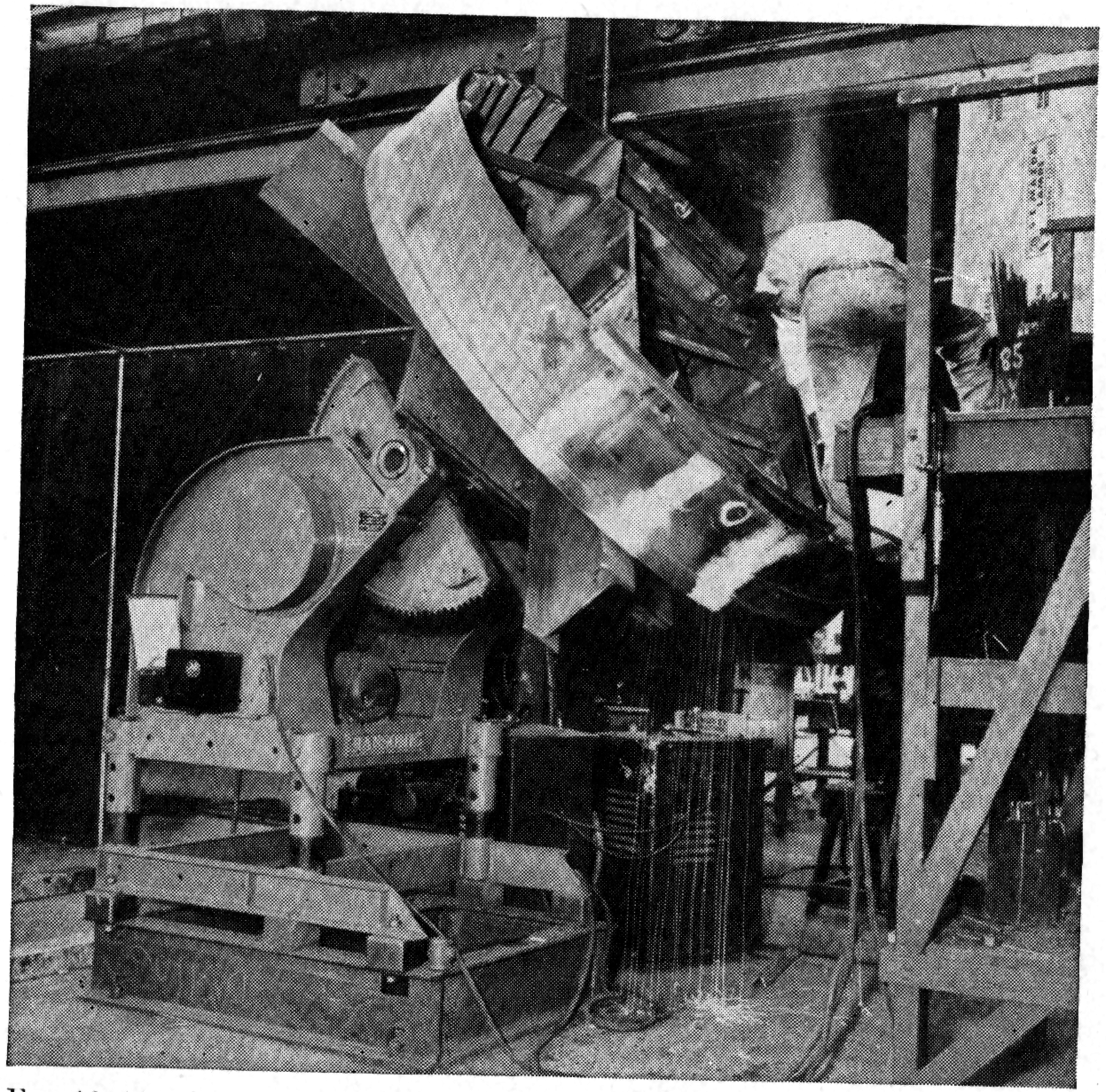


FIG. 12–11. Complex weldments are positioned as shown, to permit maximum downhand welding, to increase production, and to obtain better welds. (Courtesy of Ransome Machinery Co., Dunellan, N. J.)

12–23. Electrodes. Metallic arc welding is conducted by means of electrodes only broadly similar in composition to the base plate. Since the cross-section of the welded members may consist largely or wholly of metal furnished by the electrode (as determined by the various types of plate preparations, shown in Fig. 12–12, the selection of the electrodes is based wholly on their ability to produce mechanical and metallurgical properties in the weld at least equal to those of the base plate, when used in conjunction with proper procedures and techniques.

Metallic electrodes for welding structural types of steel are generally classified into three groups as follows: (1) bare or dust coated electrodes, (2) lightly coated electrodes, and (3) heavily coated electrodes, on which the coating varies from 8 to 12 per cent by weight.

The term "bare electrode" is applied to uncoated electrodes. These electrodes are, however, thinly coated with an oxide, or sul, and lime. The sul coating is produced by first pickling the wire in sulphuric acid and later exposing it to air to form the oxide *before* it is drawn to size. Others are dipped into lime *after* pickling and are then drawn, with the lime coating acting as a lubricant, some of which remains on their surface.

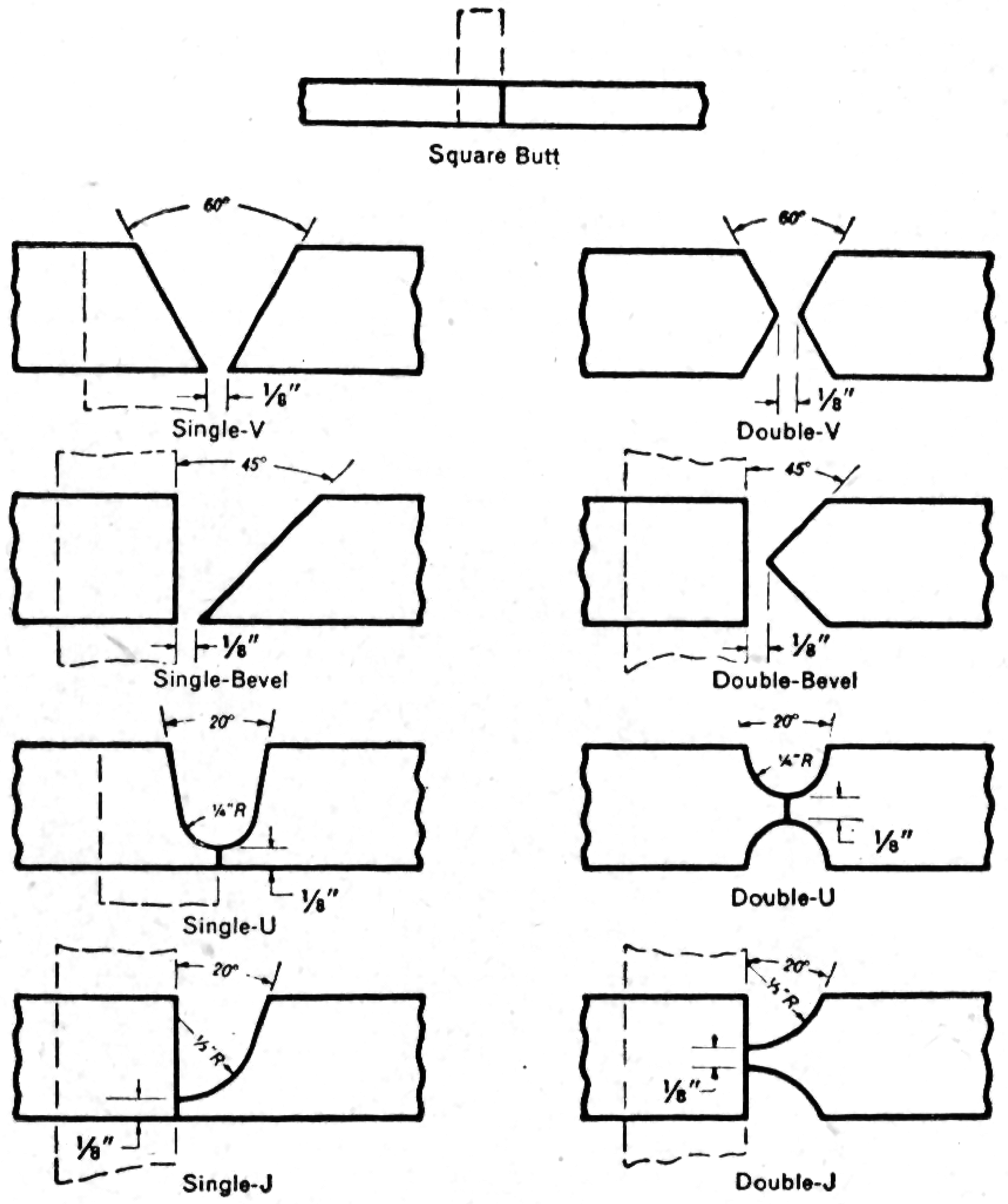


FIG. 12–12. Standard proportions of grooves for fusion welds.

These materials perform only arc stabilizing functions and furnish no protection to the molten metal against atmospheric contamination and oxidation, as do the heavily coated electrodes which are to be discussed later.

Weld metal deposited from these electrodes is inferior to structural steels and shielded arc welds in tensile strength, ductility, and particularly impact resistance, as shown in Table 12–5, and should, therefore, be used only where service stresses are largely static and not too severe.

TABLE 12–5

PHYSICAL PROPERTIES OF SHIELDED AND UNSHIELDED WELD METALS*

PHYSICAL PROPERTIES	BASE METAL	WELD METAL	
		Deposited with Metallic Shielded Arc Electrode	Deposited with Metallic Bare Electrode
Tensile strength, psi	55,000–70,000	60,000–75,000	50,000–60,000
Yield point, psi	30,000–32,000	45,000–60,000	38,000–45,000
Elongation, per cent in 2 in.	30–40	20–40	5–10
Elongation—free bend, per cent	....	35–60	10–20
Reduction in area, per cent	60–70	35–65	8–20
Density, gm/cc	7.85	7.80–7.85	7.50–7.70
Endurance limit, psi	26,000–30,000	26,000–30,000	12,000–18,000
Impact (Izod) ft lb	50–80	40–70	5–15

* *Welding Handbook* (1942 ed.).

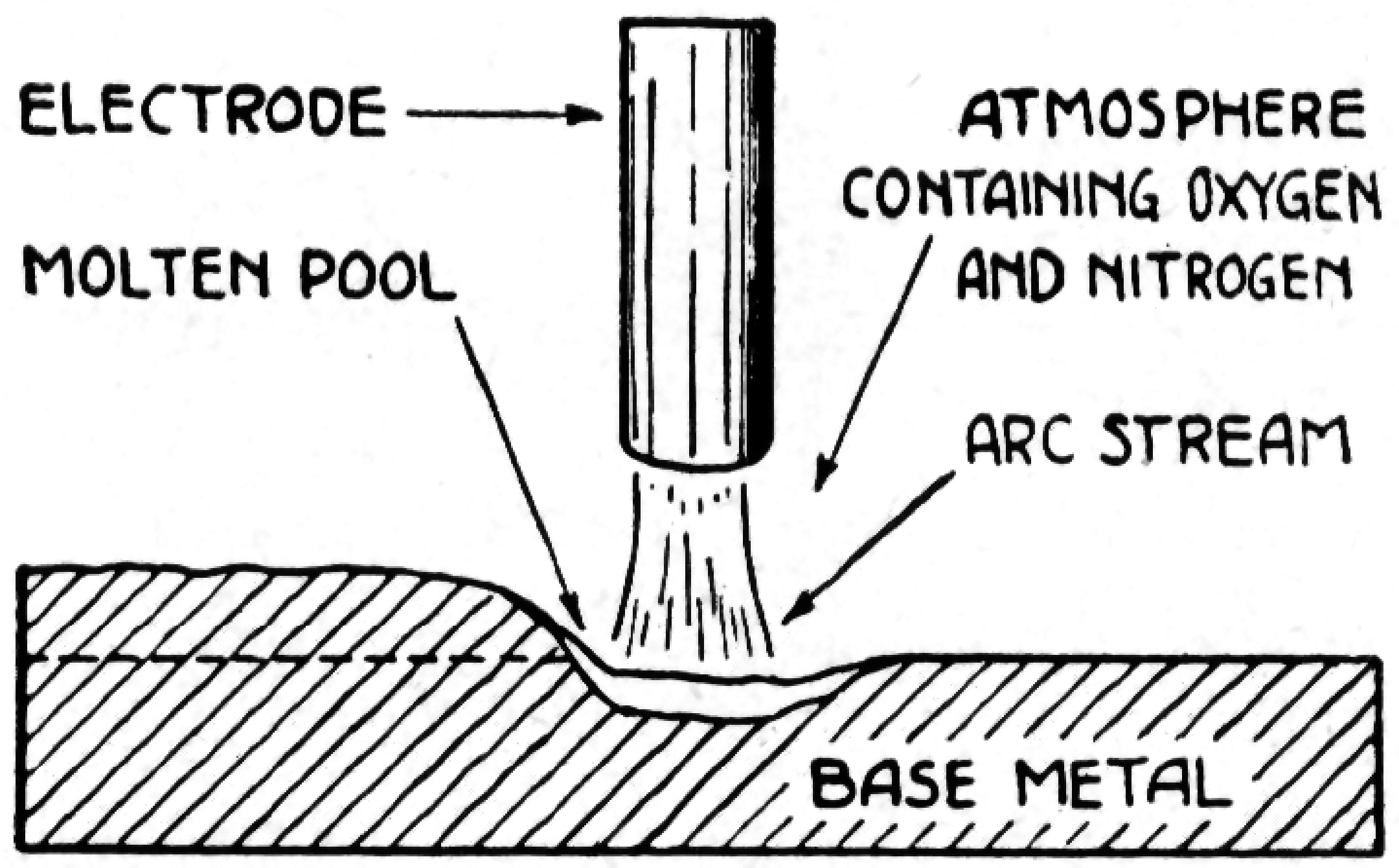


FIG. 12–13A. Unshielded arc which permits access of atmospheric gases to molten metal.

The superheated metal deposited from a bare electrode readily reacts with the ionized atmospheric oxygen and nitrogen surrounding the arc stream, as shown in Fig. 12–13A. With these, it forms compounds, such as ferrous oxide (FeO) and iron nitride (Fe_4N), which reduce the ductility and also produce age-hardening characteristics in the weld metal. Furthermore, other elements present in the electrode, such as carbon and manganese, become oxidized with the results shown in Table 12–6. The increased ductility normally resulting from a lowering of the carbon content of steel is more than offset by the high percentage of nitrogen absorbed which, while tending to increase the tensile strength, results in a corresponding decrease in the ductility.

These so-called bare electrodes may be used in all positions of welding, but only as the cathode in a d-c circuit. They are definitely unadapted for either production welding or high quality work or for parts subject to dynamic stresses.

TABLE 12-6

TYPICAL CHEMICAL ANALYSES OF SHIELDED AND UNSHIELDED WELD METAL DEPOSITED WITH SAME FILLER METAL WIRE

ELEMENT	FILLER METAL (PER CENT)	WELD METAL	
		Metallic Shielded Arc Process (Per Cent)	Metallic Bare Arc Process (Per Cent)
Carbon	.13 –.18	.08 –.15	.02 –.07
Manganese	.40 –.60	.30 –.50	.05 –.25
Silicon	.06 max.	.05 –.30	.06 max.
Sulphur	.040 max.	.035 max.	.035 max.
Phosphorus	.040 max.	.035 max.	.035 max.
Oxygen	.06 max.	.04 –.10	.15 –.30
Nitrogen	.006 max.	.010–.030	.100–.150

**Welding Handbook* (1942 ed.).

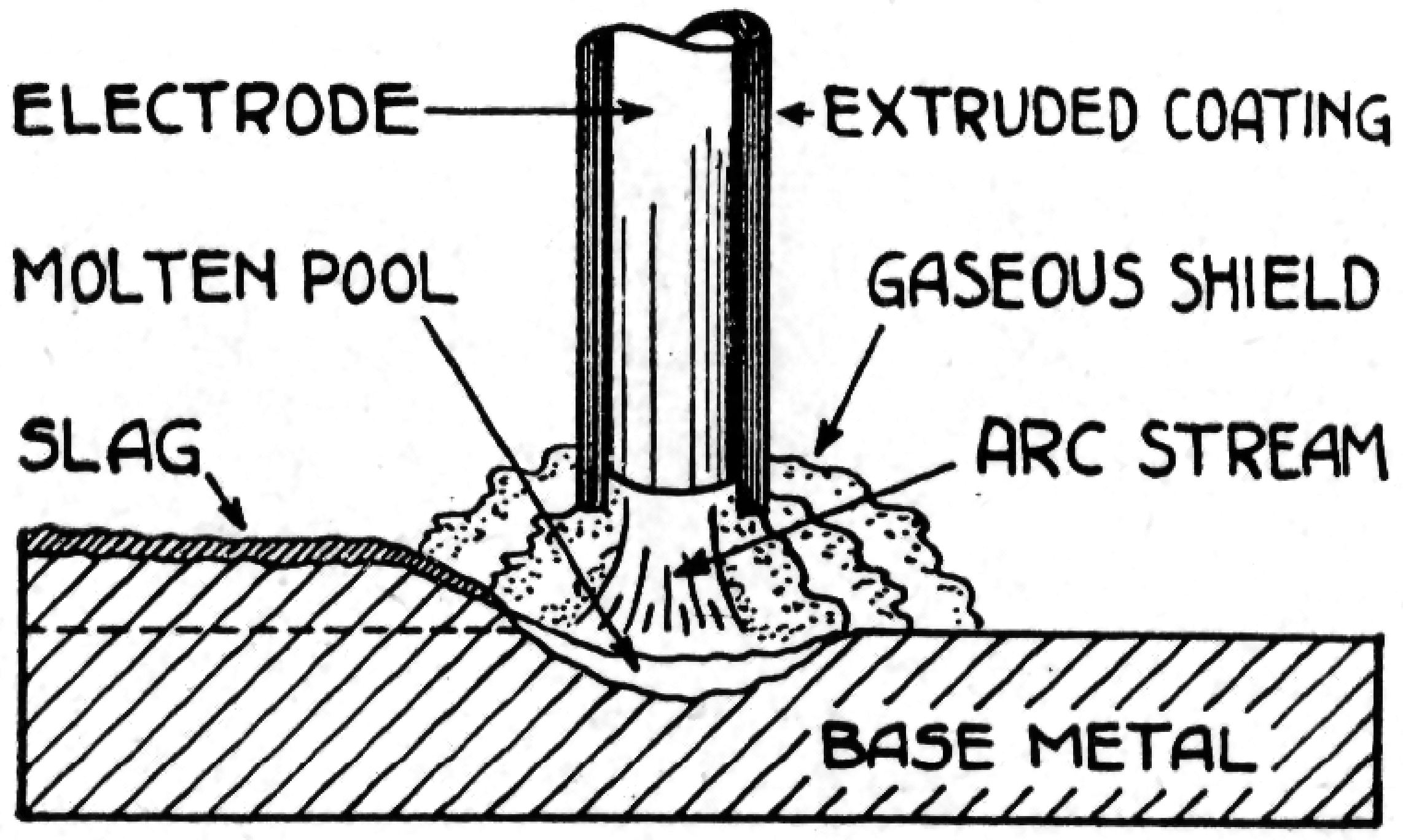


FIG. 12–13B. Influence of electrode coating on welding conditions.

The lightly or medium coated electrodes are more desirable than the sul coated ones for use in specific positions and for higher speeds, as they produce a more decided spray type of metal transference. Because of their high fluidity and melting rate, however, these electrodes are not adapted for overhead or vertical welding. Like the dust coated rod, they are used on straight polarity. As the light coating affords no protection to the molten metal, the analysis and the physical properties of the weld metal are comparable to those of the dust or sul coated electrodes.

The development of various coating compositions and their applications to metallic electrodes, more than any other factor, have made it not only possible but feasible to fabricate pipe lines, boilers, ships, tanks, bridges, buildings, and machinery of all commercial plate thicknesses by arc welding at production speeds required in modern industry with physical properties equal to or exceeding those of the base plate, as shown in Table 12–5. These electrodes may be used for welding in all positions with either direct or alternating current.

The coating ingredients usually consist of ferro-alloys, metallic oxides, and cellulosic materials and are known as the slag and gas producing type. In addition to producing large volumes of protective gases, which effectively exclude atmospheric gases from the superheated globules of metal while transferring from the electrode to the base plate, they also perform arc stabilizing functions. The less volatile materials provide a fluxing action on the molten metal, with the reaction products constituting a slag which rises to the surface and covers the deposited metal, as shown in Fig. 12–13B. This slag retards the cooling of the weld metal and therefore increases its ductility. Because of the insulating quality of the coatings, covered electrodes are well suited for welding in narrow grooves, since the current will not be short-circuited by contact with the side walls.

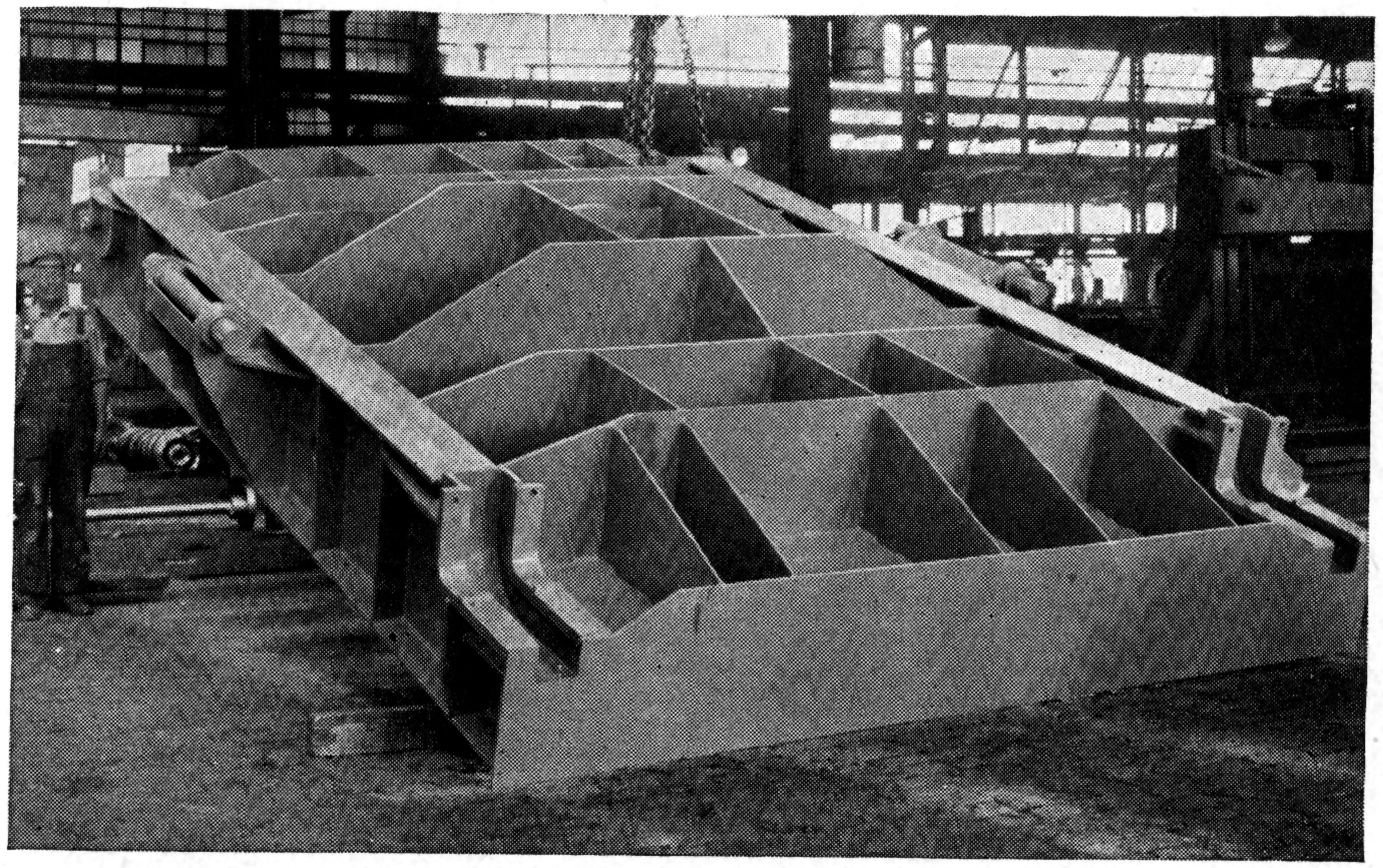


FIG. 12–14. A 60-ton completely welded trolley frame for an 86-ft span crane. (Courtesy of Cleveland Crane Co., Wickliffe, Ohio.)

Electrodes capable of producing welds in all positions with tensile strengths in structural steels ranging from 45,000 to 100,000 psi, with corresponding ductility, are available for use with either direct or alternating current. One application of electric arc welding is shown in Fig. 12–14. Procedures for welding metal of various thicknesses are shown in Fig. 12–15.

12–24. Metal Transference. The mechanics of arc welding involve first producing an arc by contacting the two conductors (plate and electrode) and then slightly separating them. This results in the immediate generation of heat, which produces a small crater of molten metal directly underneath the electrode and simultaneously melts the lower extremity or tip of the electrode. On a bare electrode, the molten metal forms a globule or "drop" of a size regulated by the surface tension of the metal; this drop elongates and separates from the electrode to become incorporated in the molten pool underneath.

Oscillographs of current during bare wire welding reveal periodic large surges of current corresponding to the number of globules of metal deposited and the momentary short-circuiting of the current. Other evidence of this characteristic is seen in the sputtering and the difficulty of maintaining a bare wire arc. The incorporating of materials in either the coating or the core wire, which reduces the surface tension of the metal, results in a corresponding increase in both the speed and the amount of metal deposited. This the commercial coated electrode does quite effectively.

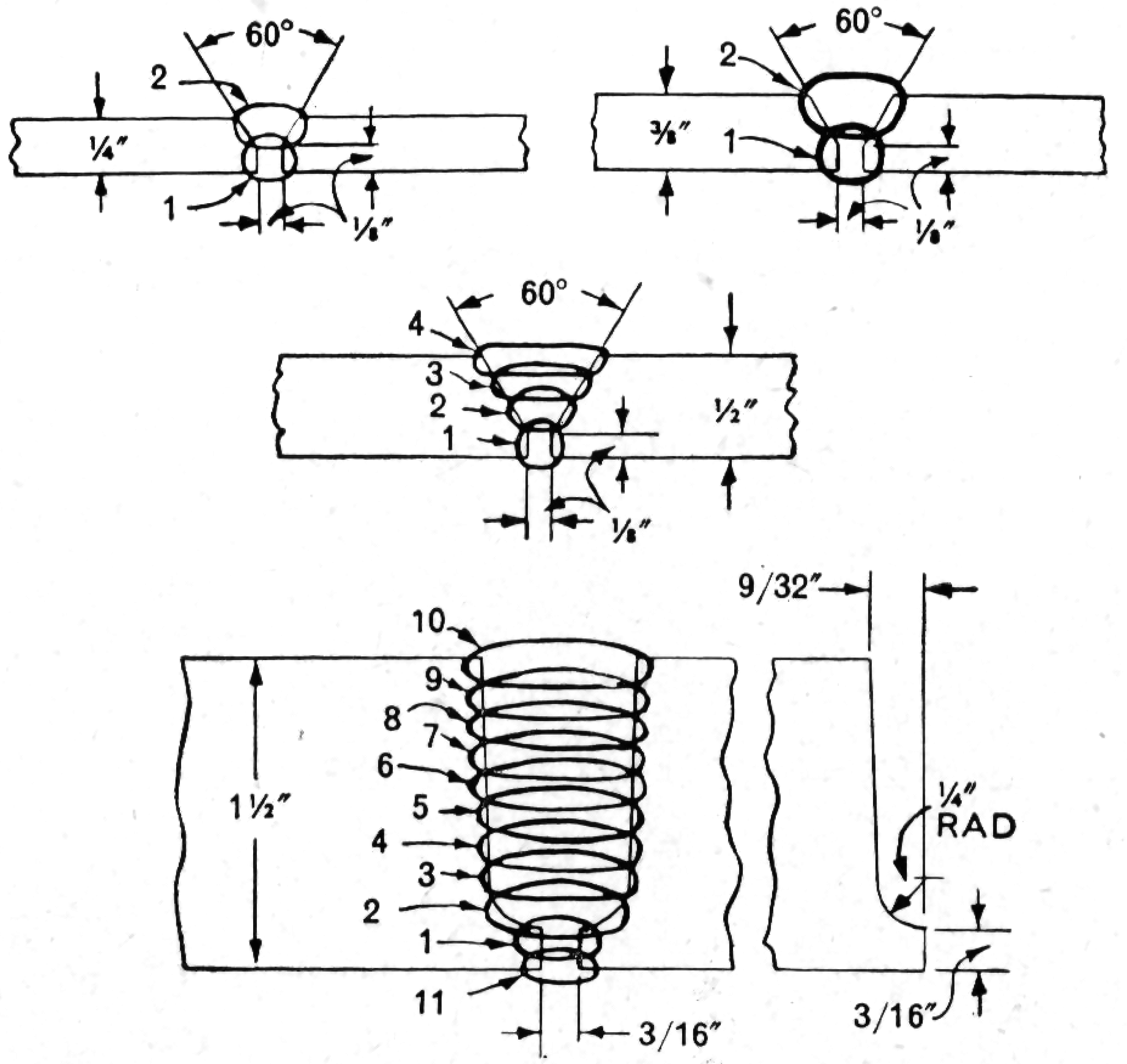


FIG. 12–15. Sequence of successive beads or layers of weld metal for various thicknesses of plate and types of joints.

Gases produced at the arc by the combustion of the constituents of the coating surround the metal as it is transferred in small globules across the gap. This is shown in Fig. 12–13B.

Opinions differ as to the forces which influence the transfer and retention of the metal on a horizontal or vertical surface or in an overhead position when the electrode is either positive or negative or when alternating current is used. Some of these forces are capillary attraction, surface tension, gravity, and expulsion by gas stream produced by coatings on the metal.

The maintenance of a steady arc is conditioned by the ease with which the gases in the gap between the electrodes or the two terminals of the electrical circuit are ionized and an electronic path is established for the electric current to flow between the conductors. Unless a large number of these *carriers* (electrons), or negatively charged particles of electricity, are liberated from some source, no arc is possible. One of the primary functions performed by the electrode coatings, which greatly facilitates welding and production, is furnishing electrons in large quantities at operating temperatures; these ingredients provide the atmosphere requisite to the uninterrupted conduction of the current. For this reason, the carbonate coated electrode performs better than a bare rod. The atmosphere enveloping the molten metal produced by the combustion of the ingredients on a heavily coated electrode consists largely of hydrogen and carbon monoxide, which have higher ionization potentials than oxygen and nitrogen in atmospheric air. Consequently, these electrodes are operated with a higher current and voltage than the bare or lightly coated electrodes, because greater energy is required to ionize the liberated gases and to melt the coating which is more refractory than the core wire. This increased energy results in higher welding speeds and increases the amount of metal deposited.

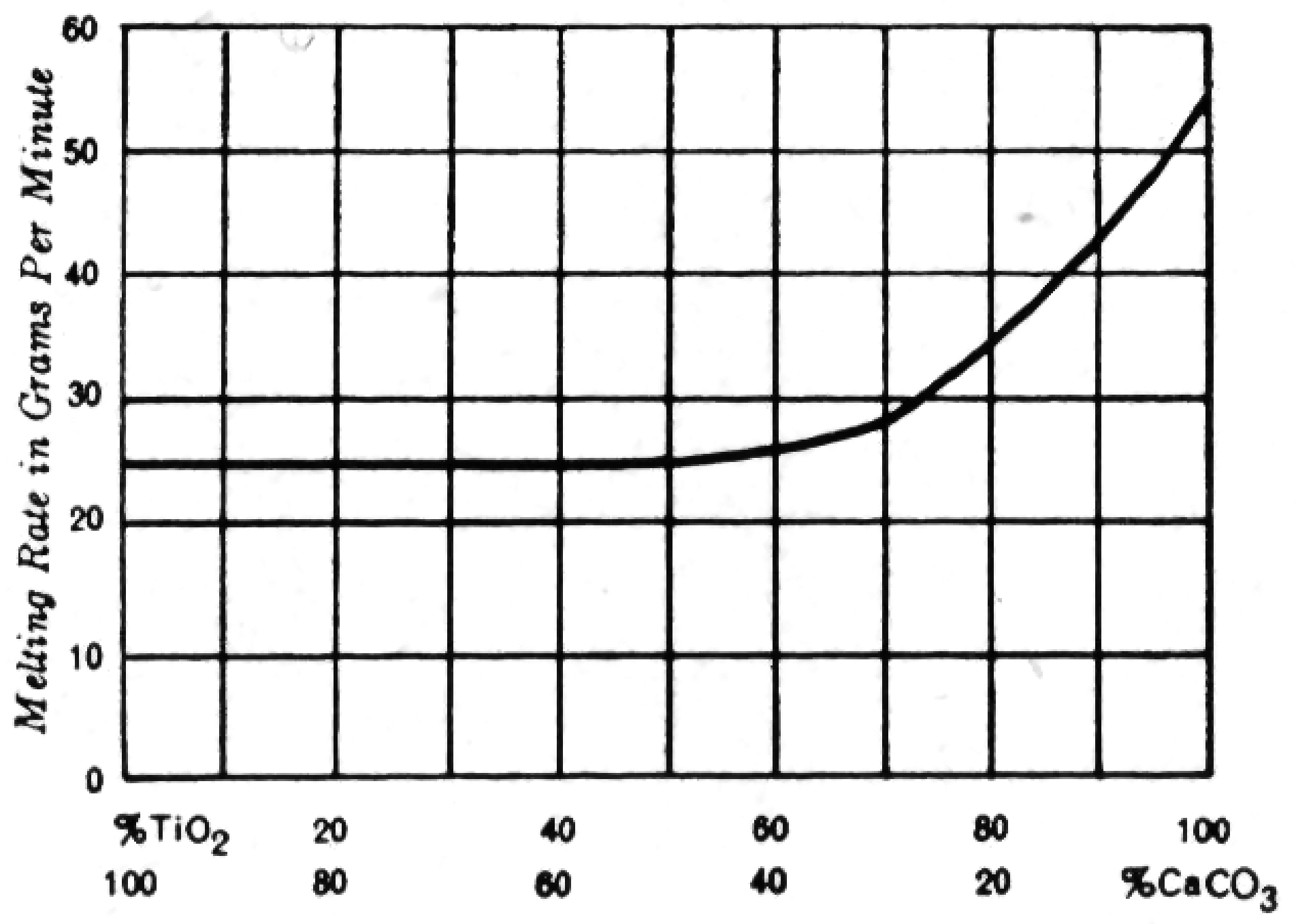


FIG. 12–16. Effect of a light flux coating upon the melting rate of a 3/16-in. diam electrode at 190 amp.

The influence of two ingredients in various amounts, incorporated as a light coating (0.001 in.) on the melting rate of 3/16-in. diam electrode used on straight polarity and 190 amp is shown in Fig. 12–16.

The specific proportions of the materials incorporated in electrode coatings are proprietary secrets. Most coatings, however, include some cellulosic materials such as wood flour, paper or cotton, ferro-alloys, and oxides such as titanium, manganese, calcium, aluminum, molybdenum, iron, and silicon. Sodium silicate is the usual binding agent.

12–25. Carbon Arc Welding. Under certain conditions hard carbon or graphite electrodes may be advantageously substituted for metallic ones as the negative terminal of a d-c circuit. The welding is then conducted with or without a filler metal in a manner similar to the oxyacetylene or the oxyhydrogen processes.

The electrode is gripped in a special holder close to the base of a tapered end to avoid overheating and vaporization of the carbon. An arc is maintained between the electrode and the base material to be welded and the filler metal is added separately in rod form.

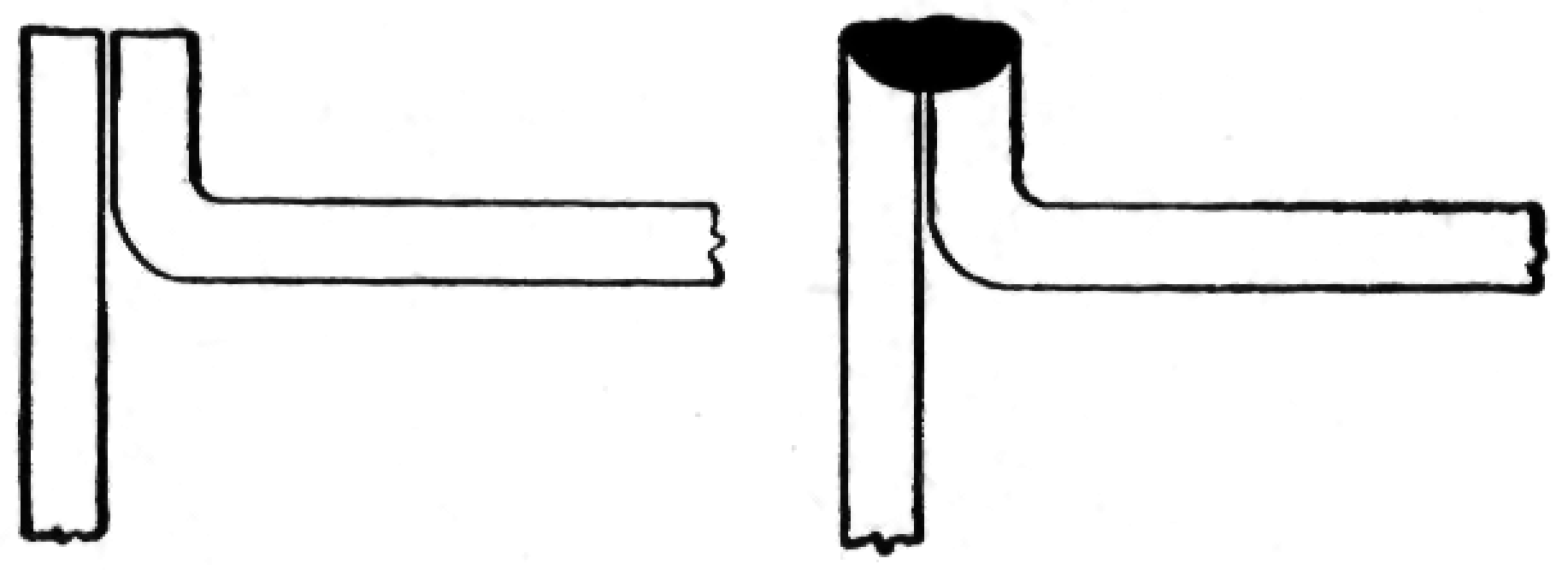


Fig. 12–17. Flange or edge welds.

TABLE 12–7

RELATION OF CURRENT AND VOLTAGE TO SPEED OF WELDING, THICKNESS OF PLATE, AND SIZE OF ELECTRODE IN AUTOMATIC CARBON ARC WELDING OF FLANGED JOINTS*

Metal Thickness (Gauge)	Arc Volts	Arc Amps	Carbon Size (In.)	Welding Speed (Ft/Hr)
20	22	120	1/4	250
18	22	120	1/4	225
16	25	120	1/4	200
14	25	140	5/16	185
12	25	275	5/16	170
10	25	325	5/16	150
3/16	25	350	5/16	140
1/4	25	350	5/16	135

* *Welding Handbook*, p. 177 (1942 ed.).

The carbon arc is particularly suited for automatic or manual welding of flanged joints or edges (as shown in Fig. 12–17) between thin sheets of plain carbon and alloy steels, including stainless alloys, aluminum, copper, and their alloys. Relative data for the welding of steel of different thicknesses are given in Table 12–7. Recent trends, however, indicate rapid expansion of the use of the atomic-hydrogen and helium arc processes for the welding of these metals.

12–26. Alternating-Current Arc Welding. The development of arc stabilizing electrodes, which permit an arc to be struck with a lower open-circuit voltage and with consequent greater safety for the operator, has in recent years caused a rapid increase in the use of variable voltage a-c welding transformers. Welds of equal quality are made with either direct or alternating current in all positions when suitable electrodes are used.

Among the advantages claimed for alternating current are (1) increased soundness of deposited metal caused by pulsations of the arc, (2) low power and maintenance costs, and particularly (3) the elimination of residual magnetism or *arc blow*. This latter condition results from a magnetic disturbance produced when current passing through a conductor causes the arc to become wild and uncontrollable, particularly when welding with heavy current in a groove. Although normally concentric to the conductor, these lines of force travel a path of least resistance and consequently may, under favorable conditions, become eccentric and exercise considerable *pull* on the arc, making progress difficult or impossible. Because of the constantly changing direction of current flow in a-c welding, these lines of force are reversed or canceled with each alternation of current. Various techniques are employed to overcome arc blow, such as changing the ground connection, welding away from the ground, or changing the angular relation of electrode and work.

12–27. Automatic Arc Welding. Mechanical provisions for the control of arc length and travel speed have made possible increased production and consistently uniform welds of high quality. Automatic arc welding devices incorporate means of controlling the consumption of electrodes and the speed of arc travel, of maintaining constant arc length, and of conducting the current to the electrode.

The welding wire or electrode is generally of the bare or lightly coated type and is consequently furnished in coils. This makes possible uninterrupted welding. When special means are used, necessitated by the insulating character of electrode coatings, it is possible to combine the advantages of automatic arc welding and the benefits of the shielded arc by using gas producing coated electrodes.

The advantages of automatic arc welding over the manual processes are that (1) less experienced operators are capable of producing consistently good welds, (2) a steady and uniform arc can be maintained, (3) the use of a coil of electrode wire makes for elimination of craters when an arc is restarted, (4) electrode stub end losses are reduced, and (5) higher production rates are provided. Its limitations are (1) lack of economy except for welding continuous lengths or long seams, (2) the necessity of providing for starting and finishing the weld with plates added to the required length of seam, and (3) the necessity of positioning fillet welds at 45 degrees with the horizontal.

12–28. Atomic-Hydrogen Welding. The atomic-hydrogen process of welding is successfully applied to the welding of thin ferrous alloys, such as those containing chromium, molybdenum, or nickel, as well as to the stainless alloys and nonferrous metals and their alloys, such as aluminum, copper, duralumin, Monel, bronze, and brass. It is also especially suitable for the repair or the modification of alloy steel dies and molds, which are used in plastics and drawing operations on punch presses, where the weld metal must conform in analysis to the parent metal in order to obtain uniformity in heat treatment. Because the operating costs are higher than those of other fusion processes, the use of the atomic-hydrogen process is restricted to the welding of metals and alloys that are difficult to weld by other means.

Basically the process consists of introducing molecular hydrogen (H_2) into an arc drawn between two tungsten electrodes attached to an a-c source. The electrodes are adjusted for heat control by the manipulation of a trigger attached to the electrode holder. Filler metal, if needed, is added independently.

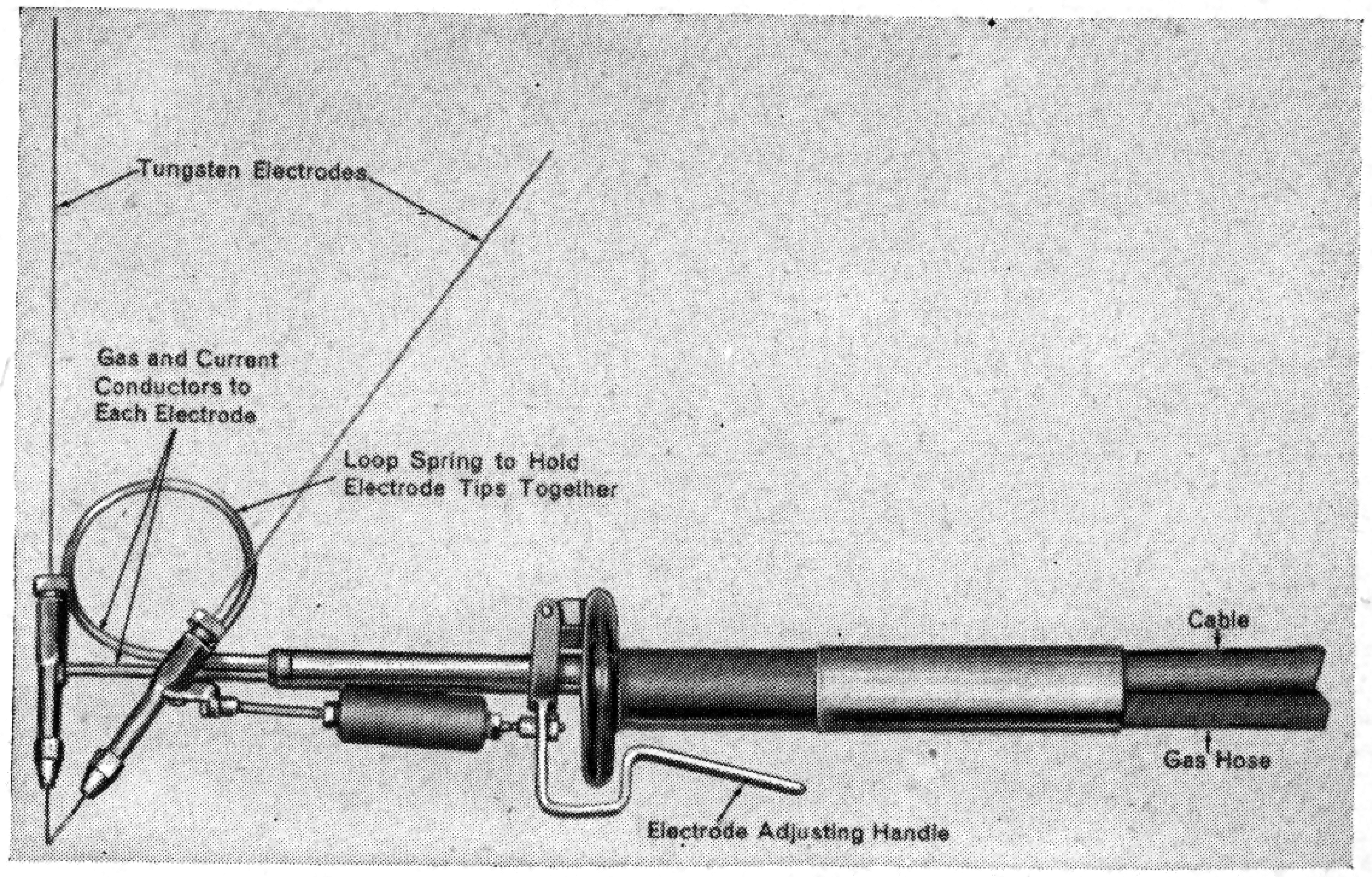

Tungsten Electrodes
Gas and Current Conductors to Each Electrode
Loop Spring to Hold Electrode Tips Together
Cable
Gas Hose
Electrode Adjusting Handle

FIG. 12–18. Atomic-hydrogen arc welding torch. (Courtesy of General Electric Co.)

When discharged into the arc, the molecular hydrogen (H_2) dissociates into individual atoms (atomic-hydrogen 2H) and absorbs a considerable amount of heat from the arc. After emerging from the arc stream, the hydrogen contacts the material being welded and the atoms recombine, liberating energy in the form of heat previously absorbed and producing a flame temperature of approximately 7000F.

The process may be operated either manually or automatically. A torch for manual welding is shown in Fig. 12–18. The current values for welding various thicknesses of metal are given in Table 12–8.

12–29. Helium Arc Welding. Helium is at present utilized for the shielded arc welding of aluminum and magnesium alloys in thin sheets. Its function is similar to that of hydrogen—to prevent the formation of oxides and metal contamination. The heat is obtained by drawing an arc between the work and a single carbon or tungsten electrode held in a torch or holder. Commercial helium of 98 per cent purity is furnished through a gas nozzle to the arc and flows down around the electrode, completely enveloping the end of the electrode and the molten metal.

Direct current furnished by standard types of d-c generators of 150- to 300-amp capacity is utilized for the helium arc process, with the work always constituting the negative terminal and the electrode the positive. The ordinary standard types of joints used in other welding processes are applicable for helium arc welding.

12–30. Influence of Welding Temperature on Metal Structures. Fusion welds, made in accordance with the correct techniques for the particular metals, most frequently fail under both dynamic and static stresses through an area some distance from the actual weld itself. One reason for this is that approved welding rods and electrodes deposit a high quality of weld metal, which possesses higher yield and tensile strength than the base metal.

TABLE 12–8

WELDING CURRENT FOR VARIOUS TYPES OF WELDS; ATOMIC-HYDROGEN MANUAL WELDING*

PLATE THICKNESS (IN.)	TYPE OF WELD			
	Lap and Fillet	Butt	Corner	Edge
1/32	15–20	15–20	15–20	20–25
1/16	20–25	25–30	25–30	30–35
1/8	30–35	35–40	35–40	40–45
3/16	35–40	40–45	45–50	50–55
1/4	45–50	50–55	55–60	60–65
3/8	55–60	55–60	60–65	60–65
1/2	70–75	70–75	70–75	70–75

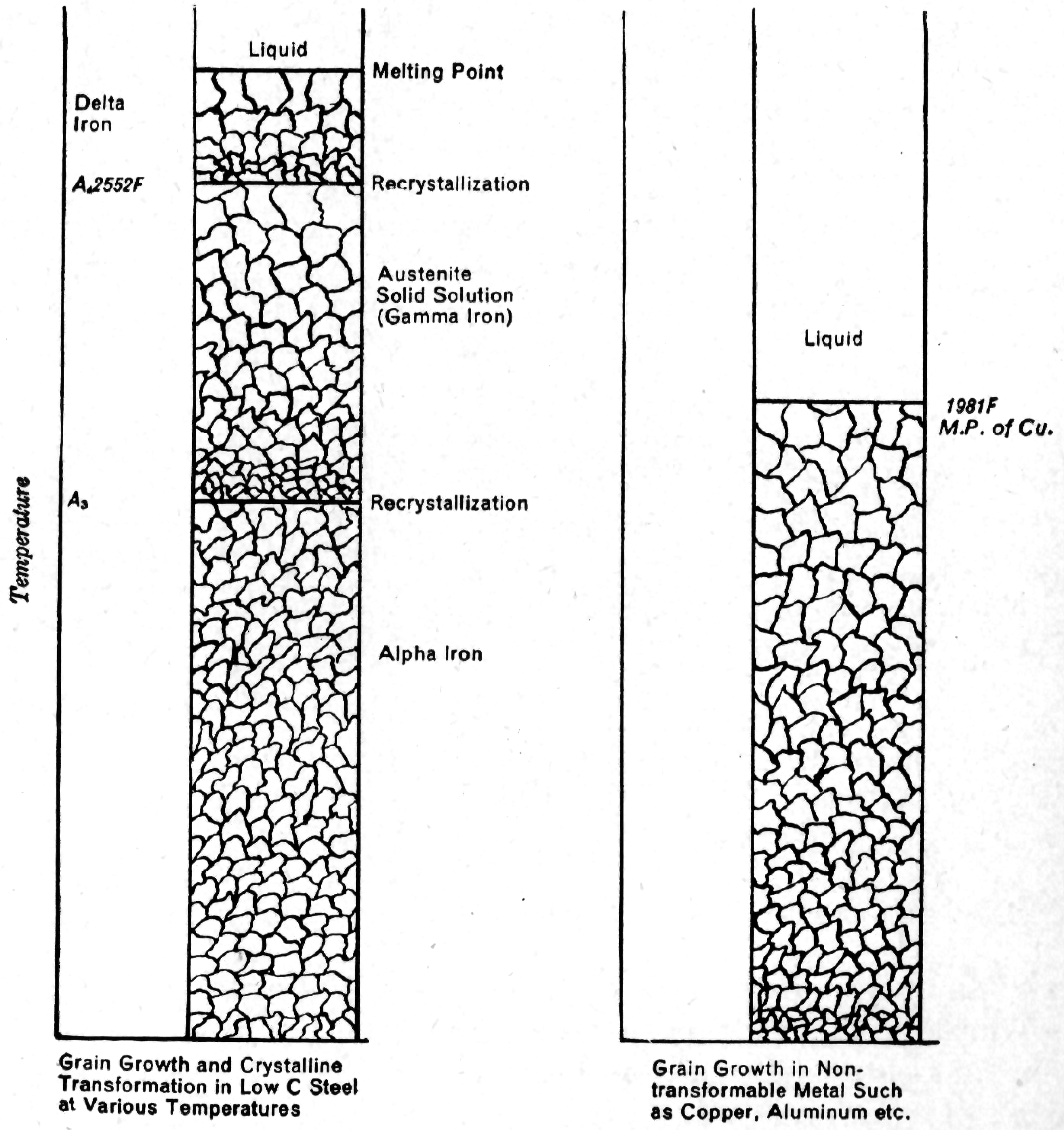
* *Welding Handbook* (1942 ed.), p. 231.

Other conditions, produced by the incidental heating to fusion of nonpressure welds in the weld area, cause metallurgical changes in the metal structure, corresponding to the respective maximum temperature attained in each zone, its duration, and its subsequent transfer rate by radiation or conduction through the metal.

The underlying causes of these structural changes lie in the recrystallization and the solution and precipitation of microconstituents in metals, which undergo allotropic transformations at different temperatures, as explained in Chapter 9. Mechanical properties of steels, as affected by heat treatment, are similarly affected by welding, since the welded member reaches a temperature varying from its initial temperature to that required to weld by fusion, with the different areas reaching intervening temperatures as determined by various conditions.

The influence of temperature on the grain size of transformable and nontransformable metals is shown in Fig. 12–19.

In a section that is transverse to a weld joint, we may obtain several transitional states of the weld and base metal ranging from the cast structure in the weld joint, where the molten metal has crystallized dendritically, to the wrought condition of the plate, and through the results of intervening temperature gradients from the austenitic grain coarsening range through the recrystallizing zone at the Ac_3 critical temperature and subcritical temperatures to that of the original base metal some distance from the weld. This is shown in Fig. 12–20.

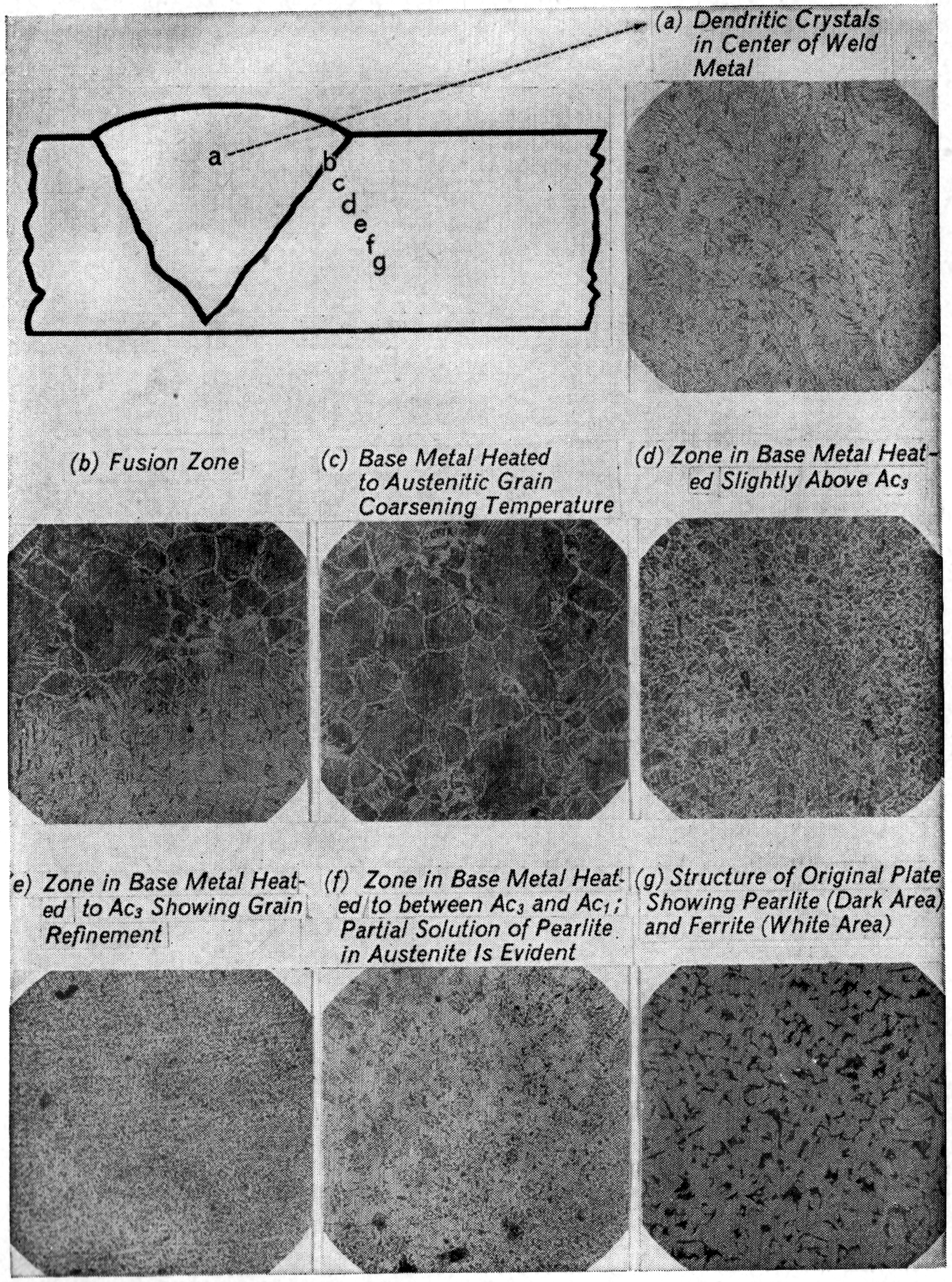


Grain Growth and Crystalline Transformation in Low C Steel at Various Temperatures

Grain Growth in Nontransformable Metal Such as Copper, Aluminum etc.

FIG. 12–19. Influence of temperature on grain size of transformable and nontransformable metals.

In summarizing, we can say that the principal factors governing structural changes in ferrous metals during welding are (1) the maximum temperature reached by the base metal, (2) the length of time



(a) Dendritic Crystals in Center of Weld Metal

(b) Fusion Zone

(c) Base Metal Heated to Austenitic Grain Coarsening Temperature

(d) Zone in Base Metal Heated Slightly Above Ac_3

(e) Zone in Base Metal Heated to Ac_3 Showing Grain Refinement

(f) Zone in Base Metal Heated to between Ac_3 and Ac_1; Partial Solution of Pearlite in Austenite Is Evident

(g) Structure of Original Plate Showing Pearlite (Dark Area) and Ferrite (White Area)

FIG. 12–20. Structural changes in a single vee arc welded plate.

the metal is held at this temperature, (3) the analysis of the metal (carbon and alloy content and type of alloy elements present) and (4) the cooling or rate of heat abstraction in the various zones. These conditions are largely controlled or determined by (1) the size of the weld section, relative to the parent metal, which determines the quantitative heat input, and consequently the area of the affected zone, (2) the welding rate, i.e., the number of welds or passes applied, (3) the current intensity or size of torch tip, (4) the welding process used, (5) the plate or weld edge preparation, (6) any preheating or postheating employed or any thermal insulating material which influences the cooling rate, and (7) the specific properties of the metal.

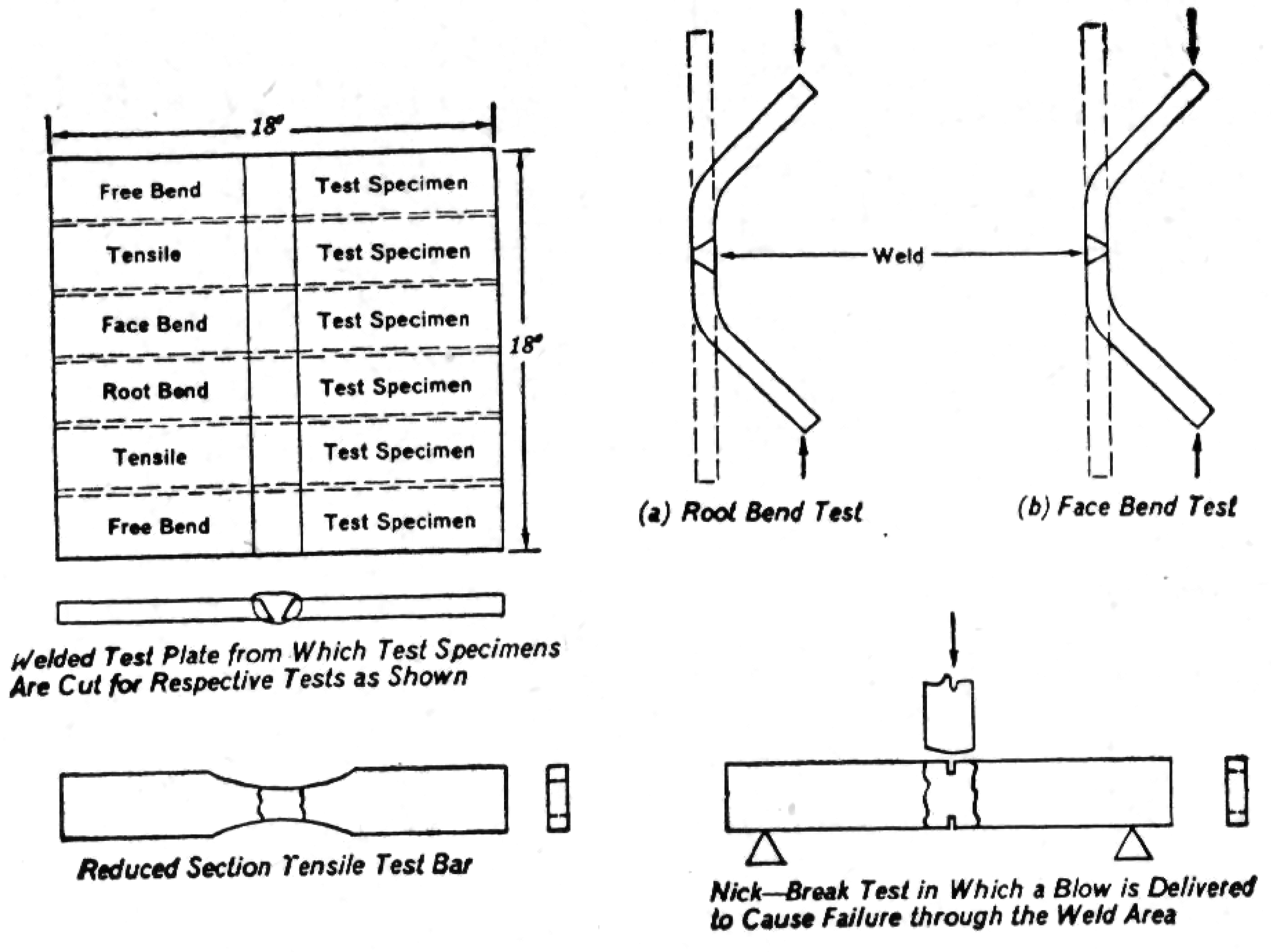
The significant metallurgical influence of the heating and cooling cycle on grades of plain carbon steels possessing good weldability (less than 0.30 per cent carbon) is merely to produce (1) a modification of the normal pearlitic distribution and (2) a coarse austenitic grain structure adjacent to the fusion zone. The effect of this on the hardness, tensile, and yield strength is inconsequential, although the fatigue or endurance limit and impact strength are slightly reduced.

The welding of steels of higher carbon and alloy content, however, involves considerations peculiar to the grade since cooling rates permissible in a plain low-carbon steel may produce microstructures and mechanical properties wholly undesirable for the service required. It is therefore important that welding procedures be adapted to the different steels, particularly in regard to the effect on the cooling rate. Since alloys decrease the rate of transformation of austenite, the slower cooling rates become increasingly critical. For this reason, the new high strength, low-alloy structural steels require care in their welding. A high or intermediate cooling rate of high-carbon steels from the welding temperature may result in the transformation of the austenite to martensite, or troostite, rather than to pearlite, with a consequent loss of ductility.

12–31. Testing of Welds and Welding Operators. In common with other forms of fabrication and manufacture, welding requires adequate and satisfactory commercial inspection methods to determine its quality and reliability. Since the basis is the production of physical properties in the weld seam or joint comparable to those of the base metal involved, the tests most commonly used are the standard mechanical tests—such as tensile, impact, shear, fatigue, and bend—as these give adequate information about both the quality of the weld metal and the ability of the operator to produce welds under certain conditions. Some of these tests are shown in Fig. 12–21. Obviously, these are destructive measures and are designed to reveal the operator's qualifications to produce welding of the quality required in bridges, tanks, ships, boilers, airplanes, etc., as well as the suitability of the materials (base and welding rod), and the techniques and procedures employed. After such qualifications have been determined, both the periodic and the final acceptance tests must be of a nondestructive nature. For this reason, radiographs by means of X-rays or gamma rays are taken of the weld seam

to detect possible inclusions and porosity, cracks, and imperfect fusion between the base and filler metal.

Methods of inspection for other purposes are varied. Plugs are trepanned or sawed out of a seam and sectioned and etched with acid; and hardness explorations are made to determine the suitability or weldability of the metal. In addition, corrosive tests, cold rolling of welded strips, magnaflux, and other tests are made for special applications.



(a) Root Bend Test

(b) Face Bend Test

Welded Test Plate from Which Test Specimens Are Cut for Respective Tests as Shown

Reduced Section Tensile Test Bar

Nick—Break Test in Which a Blow is Delivered to Cause Failure through the Weld Area

FIG. 12–21. Testing of welds.

12–32. Welding Symbols and Their Uses. Complete data relative to the execution of welds on a weldment are furnished to the welding department by means of ideographic symbols placed on the drawing by the engineering department. This scheme provides for a minimum of numerical data, explanatory notes, and specifications; and it eliminates vague and ambiguous information being given to the operator. The system is simple and the symbols make the least demand upon memory, for once they are learned they can always be correctly interpreted. These symbols are shown in Fig. 12–22. For other combinations, see "Welding Symbols," a pamphlet by the American Welding Society.

12–33. Distortion and Stresses in Welded Structures. A concentrated application of heat, as in welding, causes a localized volumetric or three-dimensional increase at, and adjacent to, the welded area commensurate with the thermal coefficient of the metal, its thickness, its heat input, etc. Provided that the members involved remain unrestrained, permanent distortion or warpage results, as shown by the examples in Fig. 12–23, since the shrinkage during the subsequent cooling does not always effect a return of the metal to its original shape and proportions.

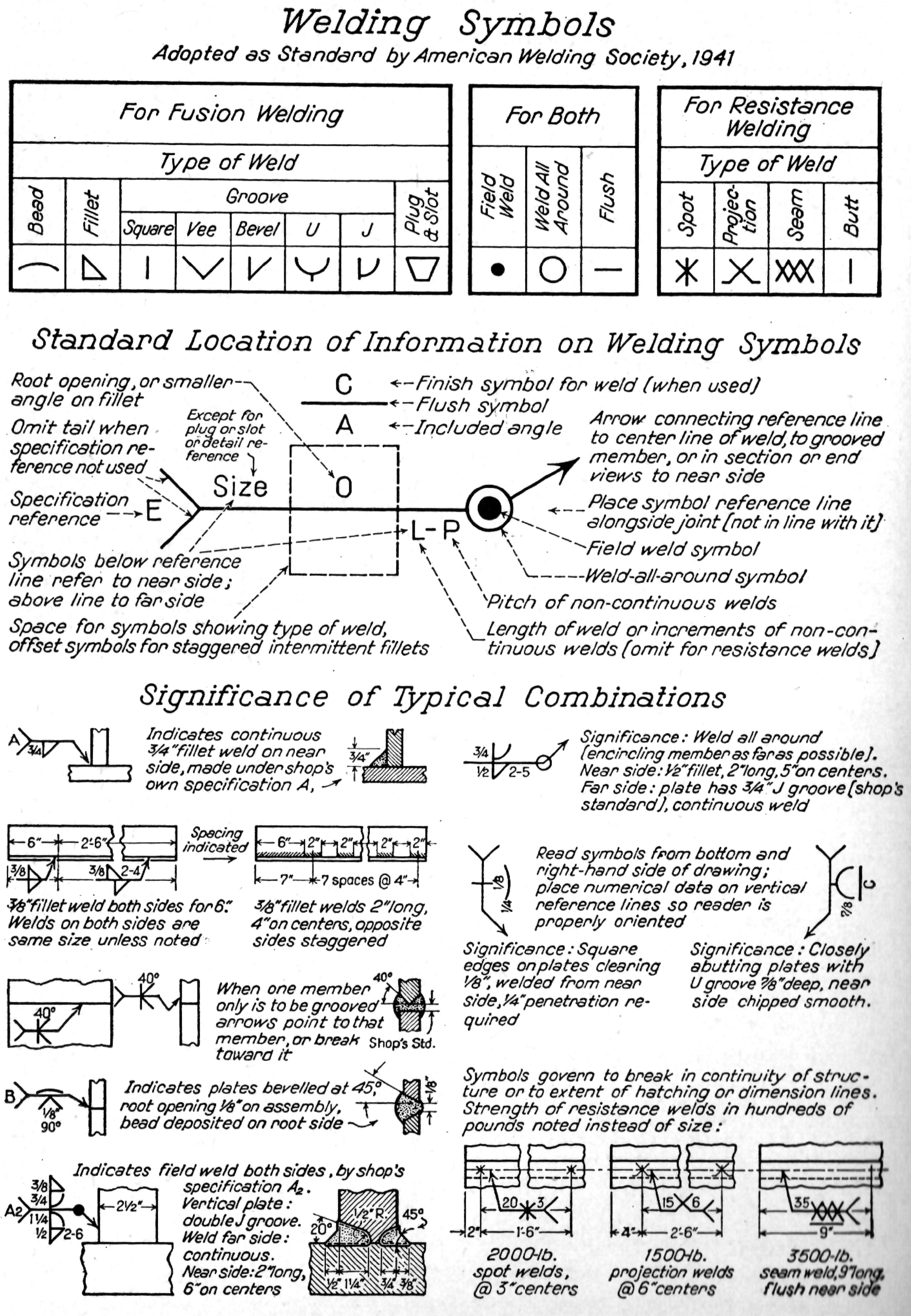
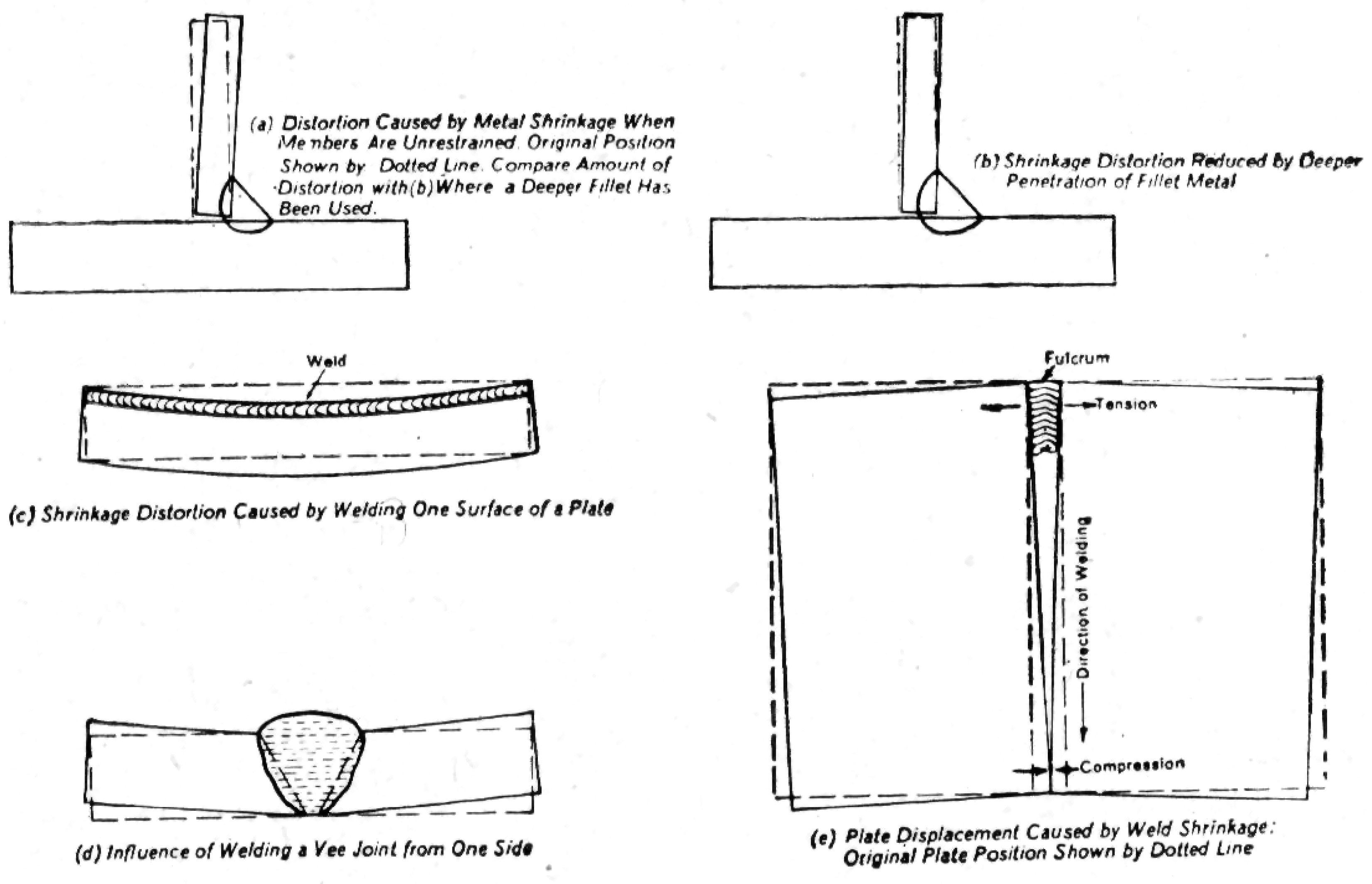

Welding Symbols
Adopted as Standard by American Welding Society, 1941
For Fusion Welding
Type of Weld
Bead
Fillet
Groove
Square
Vee
Bevel
U
J
Plug & Slot
For Both
Field Weld
Weld All Around
Flush
For Resistance Welding
Type of Weld
Spot
Projection
Seam
Butt
Standard Location of Information on Welding Symbols
Root opening, or smaller angle on fillet
Omit tail when specification reference not used
Except for plug or slot or detail reference
Specification reference
E
Size
C
A
O
L-P
Finish symbol for weld (when used)
Flush symbol
Included angle
Arrow connecting reference line to center line of weld, to grooved member, or in section or end views to near side
Place symbol reference line alongside joint (not in line with it)
Field weld symbol
Weld-all-around symbol
Pitch of non-continuous welds
Length of weld or increments of non-continuous welds (omit for resistance welds)
Symbols below reference line refer to near side; above line to far side
Space for symbols showing type of weld, offset symbols for staggered intermittent fillets
Significance of Typical Combinations
A
3/4
Indicates continuous 3/4" fillet weld on near side, made under shop's own specification A,
3/4"
3/4
1/2
2-5
Significance: Weld all around (encircling member as far as possible). Near side: 1/2" fillet, 2" long, 5" on centers. Far side: plate has 3/4" J groove (shop's standard), continuous weld
6"
2'-6"
3/8
3/8
2-4
Spacing indicated
6"
2"
2"
2"
2"
7"
7 spaces @ 4"
3/8" fillet weld both sides for 6". Welds on both sides are same size unless noted
3/8" fillet welds 2" long, 4" on centers, opposite sides staggered
1/8
1/4
Read symbols from bottom and right-hand side of drawing; place numerical data on vertical reference lines so reader is properly oriented
C
7/8
Significance: Square edges on plates clearing 1/8", welded from near side, 1/4" penetration required
Significance: Closely abutting plates with U groove 7/8" deep, near side chipped smooth.
40°
40°
When one member only is to be grooved arrows point to that member, or break toward it
40°
Shop's Std.
B
1/8"
90°
Indicates plates bevelled at 45°, root opening 1/8" on assembly, bead deposited on root side
1/8"
Symbols govern to break in continuity of structure or to extent of hatching or dimension lines. Strength of resistance welds in hundreds of pounds noted instead of size:
Indicates field weld both sides, by shop's specification A2. Vertical plate: double J groove. Weld far side: continuous. Near side: 2" long, 6" on centers
3/8
3/4
A2
1 1/4
1/2
2-6
2 1/2"
1/2" R.
45°
20°
1/2"
1 1/4"
3/4
3/8"
20
3
2"
1'-6"
2000-lb. spot welds, @ 3" centers
15
6
4"
2'-6"
1500-lb. projection welds @ 6" centers
35
9"
3500-lb. seam weld, 9" long, flush near side

FIG. 12–22. Standard welding symbols.

When welded metals are thus free of all restraint, the stress within the metal is reduced to a minimum, since the heat has produced a plastic flow of the metal and the stress set up by the heating has exceeded its elastic strength. If, however, the parts, as most commonly occurs in weldments, are rigidly held by adjoining members so that neither expansion nor shrinkage is possible, then stresses of varying magnitude and intensity depending on several factors, are introduced into the metal. One example of a shrinkage stress is shown in Fig. 12–24. Stresses resulting from shrinkage are of two general types: transverse, or shrinkage across a weld, and longitudinal, or shrinkage parallel with the weld. Transverse shrinkage in fixed plates welded on both sides, while producing no angular distortion, causes a tensile stress across the weld surface which will be proportionate to the thickness of the plates, the amount of metal deposited, and the particular shape of joint edge preparation.


(a) Distortion Caused by Metal Shrinkage When Members Are Unrestrained. Original Position Shown by Dotted Line. Compare Amount of Distortion with (b) Where a Deeper Fillet Has Been Used.

(b) Shrinkage Distortion Reduced by Deeper Penetration of Fillet Metal

(c) Shrinkage Distortion Caused by Welding One Surface of a Plate

(d) Influence of Welding a Vee Joint from One Side

(e) Plate Displacement Caused by Weld Shrinkage: Original Plate Position Shown by Dotted Line
Weld
Fulcrum
Tension
Direction of Welding
Compression

FIG. 12–23. Permanent distortion or warpage resulting from shrinkage during cooling.

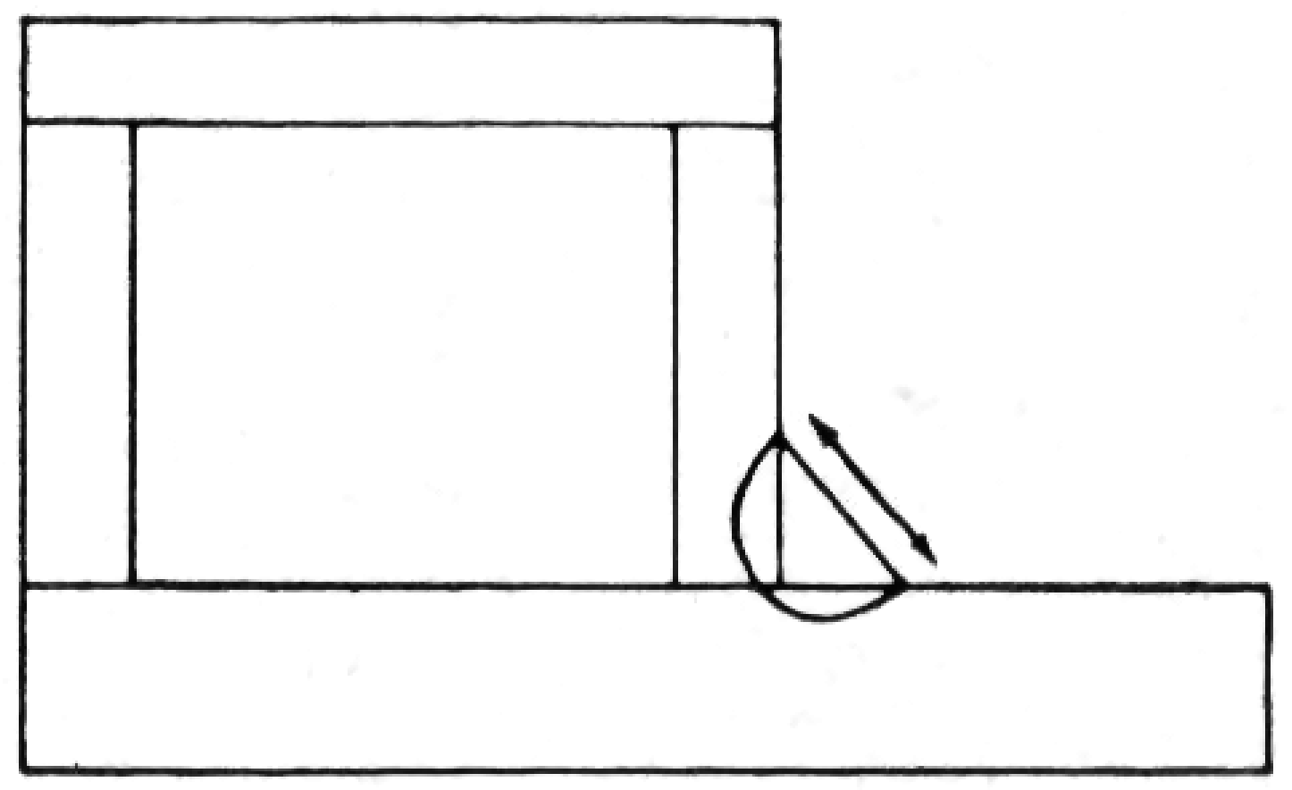


FIG. 12–24. Influence of restraint of welded members on stresses in fillet weld (shrinkage stress).

Longitudinal expansion and shrinkage in fixed plates are resisted by the plate metal adjacent to the weld with the results shown in Fig. 12–25.

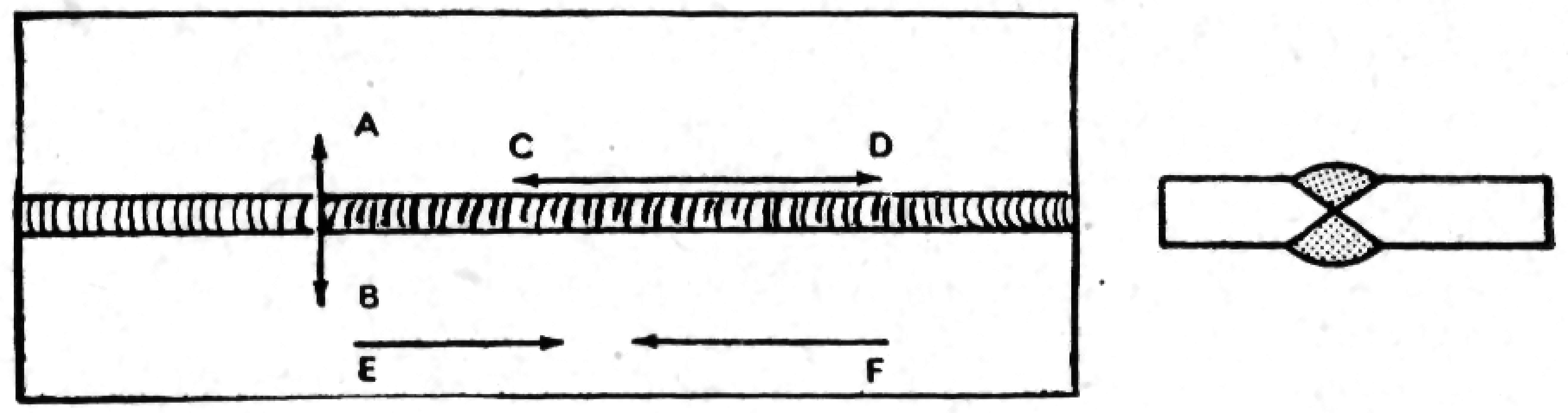


FIG. 12–25. Plates are restrained on all axes. Shrinkage causes high tensile stress across weld joint, as shown at *AB*. Longitudinal shrinkage along weld seam resisted by plate, causing tensile stress in weld, as shown at *CD* and compression stress in plate, as shown by *EF*.

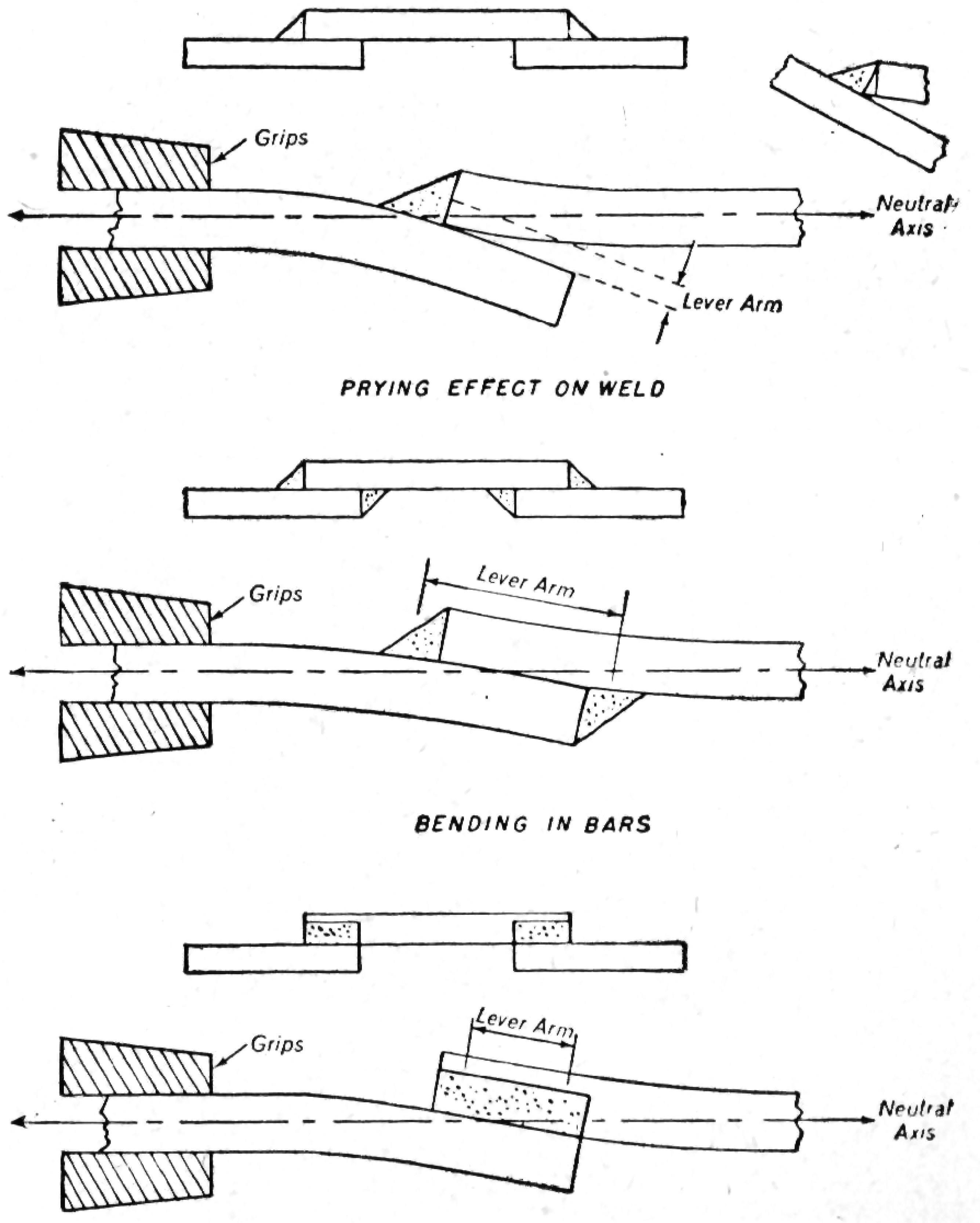

Grips
Neutral Axis
Lever Arm
PRYING EFFECT ON WELD
Grips
Lever Arm
Neutral Axis
BENDING IN BARS
Grips
Lever Arm
Neutral Axis

FIG. 12–26. Influence of lack of symmetry on distortion of welded joints under load.

As the unit strain, or elongation, across a weld at ordinary working stresses and temperature is practically zero, it is assumed that the members in a welded structure cannot move or yield sufficiently to relieve the stress. This results in what is known as residual or locked-up stresses. Provision is made, however, to stress-relieve certain weldments, such as boilers, high-pressure vessels, gun mounts, and other important parts, by heating the units after welding to a temperature of about 1150 to 1200F and cooling slowly.

Various measures employed to counteract shrinkage, distortion, and residual stresses are (1) preheating the entire assembly, (2) using jigs or fixtures to hold the components, (3) peening or hammering the weld metal with a blunt-nosed tool operated by an air hammer, (4) prespacing or prebending an amount equal to the anticipated movement, (5) placing small tack welds intermittently along the weld seam to hold plates, (6) using large electrodes, (7) using the minimum number of welds or passes, (8) following a proven welding sequence, (9) using the minimum weld deposit consistent with strength requirements, and (10) adopting a symmetrical design, which utilizes types of welds which have low inherent stresses. The influence of incorrect joint design is shown in Fig. 12–26. Some types of defects resulting from incorrect practice are shown in Fig. 12–27.

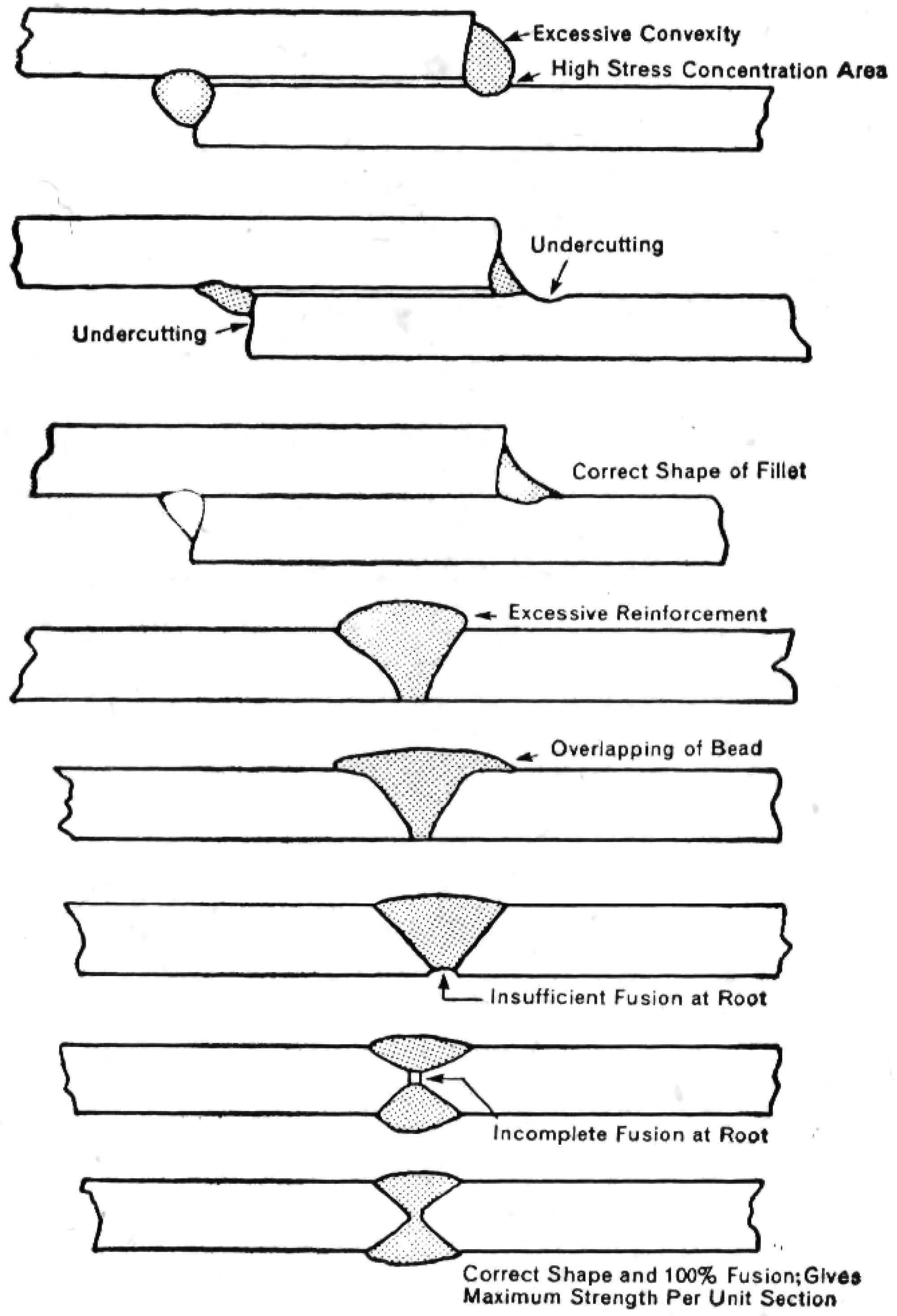

Excessive Convexity
High Stress Concentration Area
Undercutting
Undercutting
Correct Shape of Fillet
Excessive Reinforcement
Overlapping of Bead
Insufficient Fusion at Root
Incomplete Fusion at Root
Correct Shape and 100% Fusion; Gives Maximum Strength Per Unit Section

FIG. 12–27. Some types of weld joints and factors affecting their strength and efficiency.

12–34. Permissible Unit Stresses in Welds. Unit stresses utilized in the design of arc welded structures depend on the type of joint, the type of loading anticipated, the purpose of weldment, the characteristics of the steel, the operating or working temperature of the weldment, and the type of electrode used. Where no code requirements define permissible unit stresses, the designing engineer determines what stresses shall be provided for on the basis of considerable experimental data, which is available to him.

In accordance with sound engineering practice, lower unit stresses are applied to elements of machinery subjected to dynamic stresses than to those subjected to static loading. Likewise, permissible unit stresses for the higher tensile-yield strength steels are of necessity higher than for mild-carbon steels. Over 25 per cent higher permissible unit stresses may safely be allowed when the welding is done with the shielded metallic arc instead of with a bare electrode. Operating temperatures also play an important role, since high temperatures lower the tensile strength of steel and low temperatures reduce its ductility and impact strength.

The commonly accepted permissible unit stresses for fillet welds, when made with a shielded metallic electrode, is 13,600 psi for tension, compression, and shear. The strength of Vee butt joints of 100 per cent penetration is the net cross-sectional area of the weld throat multiplied by 16,000 lb for tension, by 14,000 lb for shear, and by 18,000 lb for compression. The safe allowable loads for fillet welds are given in Table 12–9.

TABLE 12–9

SAFE ALLOWABLE LOADS FOR FILLET WELDS MADE BY SHIELDED ARC PROCESS*

Size of Fillet Weld (In.)	*Pounds per Linear Inch*
⅛	1,250
³⁄₁₆	1,875
¼	2,500
⁵⁄₁₆	3,125
⅜	3,750
½	5,000
⅝	6,250
¾	7,500

**Procedure Handbook of Arc Welding Design and Practice* Lincoln Electric Co., Cleveland, Ohio.

The size of a fillet is the length of the leg *H* of the largest inscribed right isosceles triangle, as shown in Fig. 12–28. The area of the fillet per unit length is equal to *H* times 0.707 or the cos of 45 degrees.

Coinciding with the development of shielded arc electrodes, the marked trend during the past few years has been toward extensive substitution of welding for castings and riveting in all lines of manufacture. Among the inherent advantages of welding are: (1) permanent tightness of joint, (2) reduction of weight and saving of material, (3) consistent production of welds with strengths exceeding those of base metal, and (4) applicability of welding to metals of all commercial thicknesses.

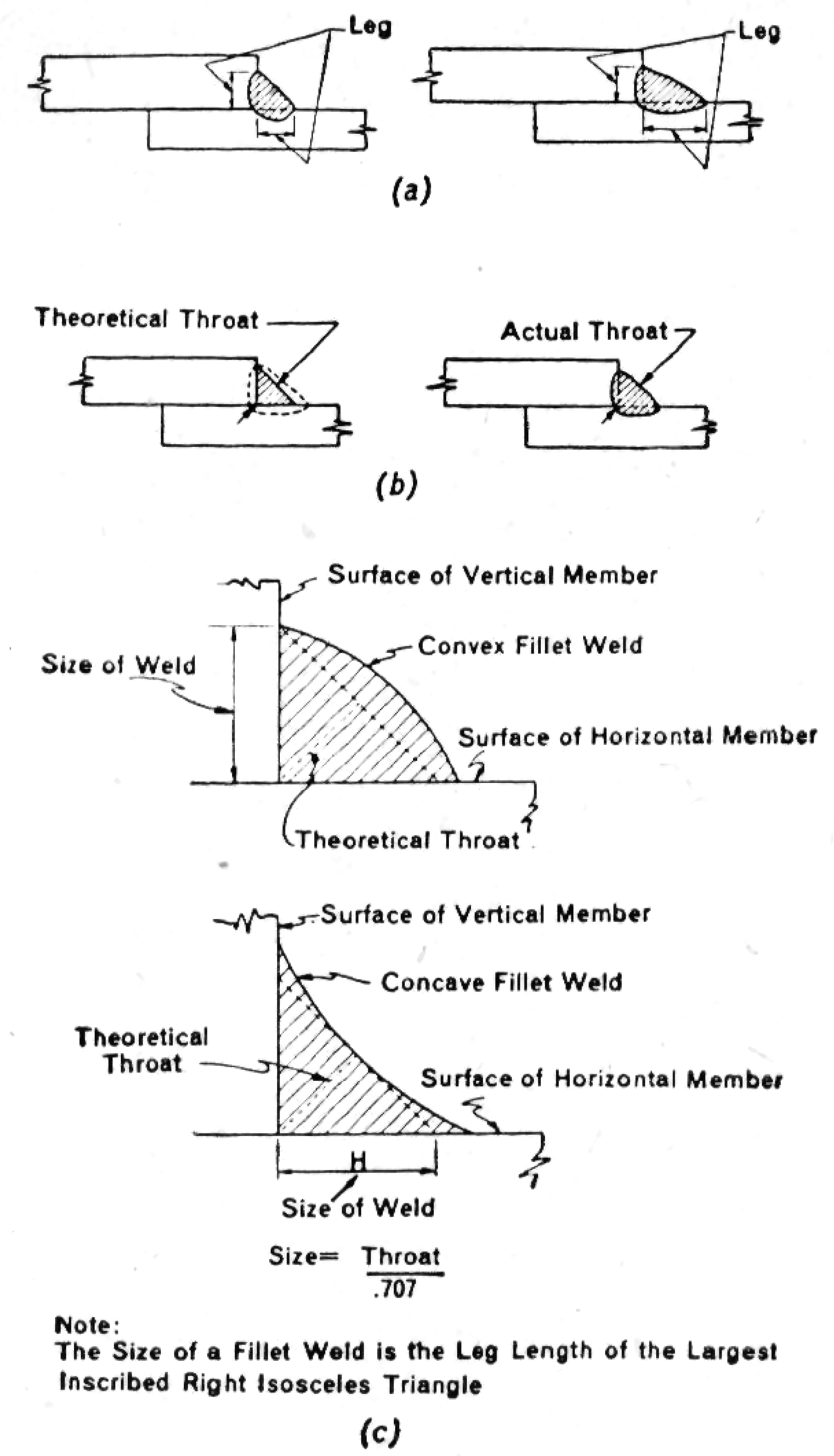

Leg
Leg
(a)
Theoretical Throat
Actual Throat
(b)
Surface of Vertical Member
Convex Fillet Weld
Size of Weld
Surface of Horizontal Member
Theoretical Throat
Surface of Vertical Member
Concave Fillet Weld
Theoretical Throat
Surface of Horizontal Member
H
Size of Weld
Size= Throat/.707
Note:
The Size of a Fillet Weld is the Leg Length of the Largest Inscribed Right Isosceles Triangle
(c)

FIG. 12–28. At (*a*), leg of fillet weld; at (*b*), throat of fillet weld; and at (*c*), size of fillet weld.

The relative length of fillet weld required to replace rivets of various diameters is shown in Table 12–10.

TABLE 12–10

LENGTH OF FILLET WELD TO REPLACE RIVETS*

RIVET DIAM. SIZE (IN.)	RIVET SHEAR VALUE AT 12,000 PSI	LENGTH OF FILLET WELDS (IN IN. TO NEAREST ⅛ IN.)									
		¼-In. Bead		⁵⁄₁₆-In. Bead		⅜-In. Bead		½-In. Bead		⅝-In. Bead	
		Fusion Code	Shielded Arc	F.C.	S.A.	F.C.	S.A.	F.C.	S.A.	F.C.	S.A.
½	2,356	1½	1¼	1¼	1	1	⅞	⅞	¾	¾	⅝
⅝	3,682	2⅛	1¾	1¾	1⅜	1½	1¼	1⅛	1	1	⅞
¾	5,301	3	2⅜	2⅜	2	2	1¾	1½	1¼	1⅜	1⅛
⅞	7,216	3⅞	3⅛	3⅛	2½	2⅝	2⅛	2	2¾	1¾	1⅜
1	9,425	5	4	4	3¼	3⅜	2¾	2⅝	2⅛	2⅛	1¾

**Procedure Handbook* (5th ed.), Lincoln Electric Co., Cleveland, Ohio.

12–35. Design of Welded Joints. Because of its flexibility and adaptation for welding metals of all commercial thicknesses in the flat, vertical, and overhead positions, the shielded metallic arc process is incomparably the most widely used for the fabrication of structural steel buildings, bridges, boilers, tanks, ships, etc. Welding procedures, specifications, and allowable working stresses covering this type of welding are, therefore, based on extensive experience and experimental data in the use of arc welding.

The strength and efficiency of a fusion-welded joint, by whatever process it is accomplished, is conditioned not alone on an adequate and thorough fusion of the plate edges and the filler metal, sufficient penetration, absence of porosity and slag inclusions, but to an equal degree on the proper design of the joint—its shape, size, location, and length. Such a factor as the inherent rigidity of a welded joint, in contrast to the slight slippage and yielding under stress of a riveted connection, makes imperative a careful analysis of joint detail with a view to minimizing the internal stresses, providing for a maximum transfer of stress between component parts, avoiding areas of high local stress concentration in and around the joint, and providing for a symmetrical or balanced distribution of the members about the neutral axis.

12–36. Fundamentals of Resistance Welding. *Definition.* A welding process, in which pressure is applied to a localized area that is heated to a welding temperature by resistance to the conduction of an electric current within the metal or between contact surfaces of two or more parts, is known as resistance welding. In contrast to most forms of welding, no filler metal is needed; and, because of the intimate contact between the weld surfaces, no fluxes are necessary to remove or prevent oxides. As a consequence, the metallurgy of resistance welding is relatively simple.

12–37. Heat Requirement Formula. As the heat is evolved within the metal (or metals), the speed of welding is determined by the rate at which heat is generated within the desired area. In any resistance welding process, the basic formula expressing the heat requirement is $H = I^2RT$, in which I = the current in amperes, R = the resistance of the work in ohms, T = time of current flow.

The three fundamental variables affecting this formula are time, pressure, and current; and resistance welding machines must be equipped to control these factors in some way.

It is seen from the formula that the current requirement to weld any metal or metals varies inversely as their resistance. Therefore high conductivity metals—such as copper and silver and, to a lesser degree, aluminum—are difficult to weld because they require a large amount of current as well as its rapid application to the weld area. Other metals—such as plain carbon and low-alloy steels, stainless alloys, Monel, silicon bronzes, and similar metals of higher resistance—are relatively easy to weld.

12–38. Resistance Factors. Factors which affect the resistivity (and welding) in any resistance welding process are: (1) resistance between the electrodes and work or parts being welded, (2) resistance between the contact surfaces of the metals, (3) specific resistance of the metals, (4) surface condition of metals (rough or smooth), (5) cleanliness of metal surface (freedom from oils, paint, or oxides), (6) shape and size of electrode, (7) surface condition of electrode, and (8) electrode material.

12–39. Heat and Current. The volume of heat required to produce sufficient plasticity to effect welding varies directly as the thickness of the metal being welded, its specific heat, and the heat losses by conduction or radiation.

By whichever method it is applied, the pressure must be sufficient to force the metals into intimate contact, to restrict the current to the weld area, and to avoid weak welds caused by porosity.

The primary current for all resistance welding processes is obtained from electrical lines of commercial voltages (220 or 440 v). After passing through a suitable transformer, the current is stepped down to high current of low potential. A diagram of an electrical circuit for resistance welding is shown in Fig. 12–29.

12–40. Classification. Resistance welding processes are divided into four main groups, each of which may be subdivided further because of special application. The principal processes are spot, roller seam, projection, and butt-flash welding.

12–41. Spot Welding. In its many diversified forms, spot welding is the simplest of all resistance welding processes and the most widely used. Basically it consists of clamping two or more sheets or strips of metal that are to be welded between two copper alloy electrodes or welding tips which are attached, on standard type machines, to conducting arms or horns through which the necessary current and pressure are applied to execute the weld. The diagram in Fig. 12–29 shows the principal parts of a spot welder.

The low potential current passing through the conductors is localized at the electrode contact surface; there it enters into the metal and is converted into heat by resistance at the juncture of the metals. The simultaneous application of the required pressure induces union of the metals in a small area directly between the electrodes.

Portable spot welders, operated hydraulically or by air pressure, are used for welding thin sheets in large assemblies, such as automobile bodies, fenders and hoods, and similar parts moving along production lines. For faster production and for large units (panels for railroad coaches, filing cabinets, refrigerators, etc.), multiple-electrode spot welders are used in which the electrodes perform the dual functions of holding down the work and conducting the current, which is rapidly switched from one electrode to the other.

Secondary currents, generally required to weld clean cold-rolled steel, vary from 1,000 to 12,000 amp, depending upon the thickness of the metal and the current "on" time. Depending on the electrode tip diameter, the recommended approximate pressures for welding this metal may vary from 100 lb for sheets 0.010 in. thick to 4,500 lb for 0.375-in. plate.

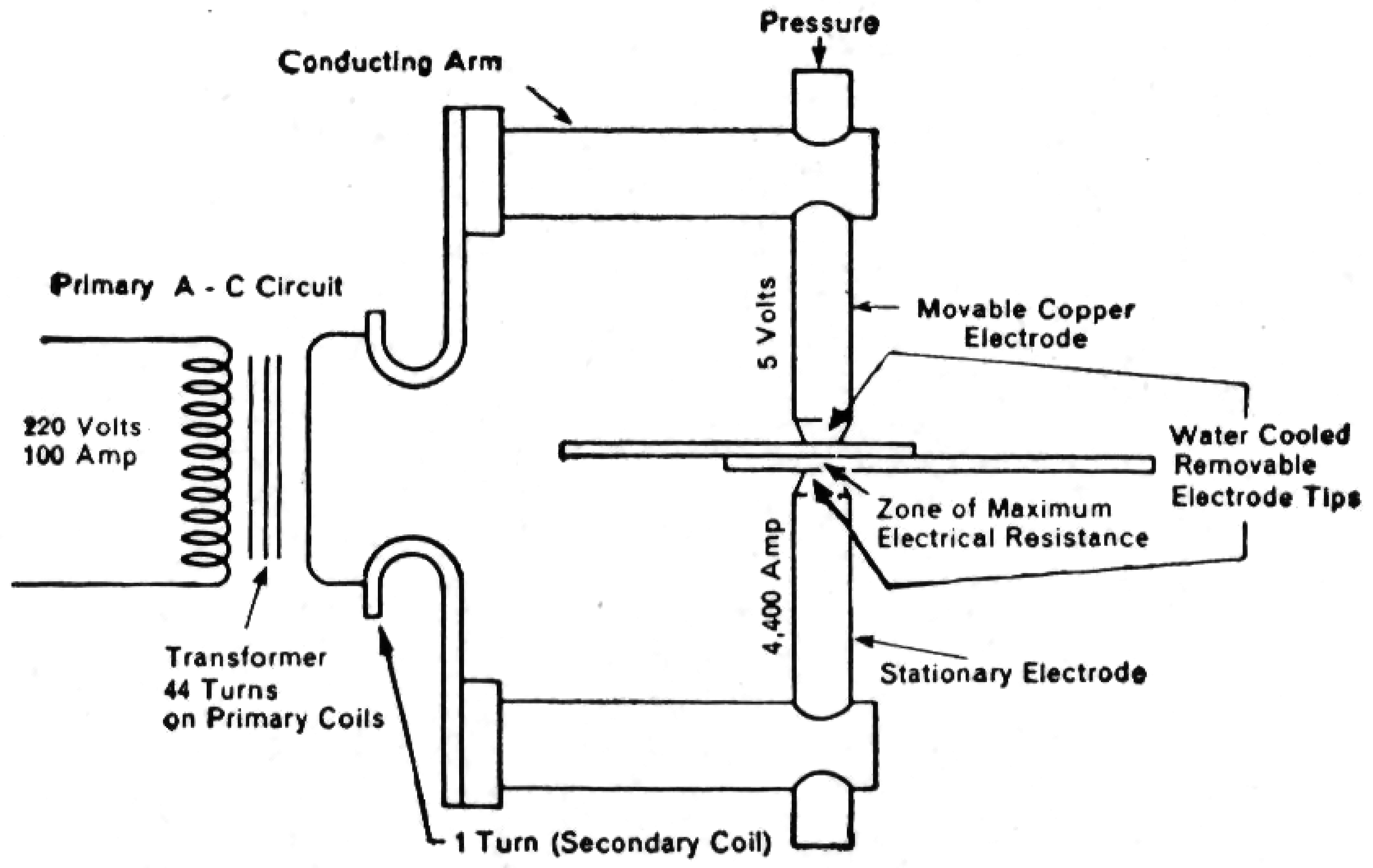


FIG. 12–29. A spot welding circuit and its application.

12–42. Weldable Metals. Generally, only the thinner metals lend themselves to spot welding. Plates up to ½ in. thick can be spot welded, however, with special techniques and machines of sufficient current capacity. The metals most frequently and easily welded are low-carbon and alloy steels, certain types of coated steels such as tin, zinc, nickel, and cadmium plated, and also stainless steels, aluminum, magnesium, nickel and their alloys, and copper, brass, and bronze. Many dissimilar metals may also be welded. Metals whose surfaces are protected with nonmetallic coatings such as enamel and paint cannot be welded.

12–43. Roller Seam Welding. Seam welding is a means of producing spot welds in overlapping sheets by contact of circular, water-cooled, rotating electrodes through which current and pressure are applied. The various factors governing the application of spot welding apply also in seam welding. Fundamentally, the process consists of making a series of spot welds sufficiently close together to constitute a continuous liquid- or gastight joint. The spots may be as far apart as may be desired. To assure more accurate control over the heat input, heat effect, and distortion of the metals, the current is periodically interrupted for most seam welding by means of various types of automatic electronic timing devices.

Pressures, speeds of welding, and spots per minute with various sizes of electrodes are given in Tables 12–11, 12–12, and 12–13.

TABLE 12–11

PRESSURE VALUES AND WHEEL FACE WIDTHS FOR SEAM WELDING LOW-CARBON STEEL WITH INTERRUPTED CURRENT*

SHEET THICKNESS (IN.)	WELDING WHEELS		WHEEL PRESSURE (LB)
	Diam (In.)	Face Width (In.)	
0.031	8	5/32	600
0.039	8	3/16	600
0.049	8	7/32	750
0.062	8	1/4	750
0.078	8	1/4	900
0.109	8	9/32	1,000
0.125	8	5/16	1,200

*_Welding Handbook_ (1942 ed.).

TABLE 12–12

TYPICAL VALUES OF CURRENT "ON" AND "OFF" TIME FOR SEAM WELDING DIFFERENT STOCK THICKNESSES AT DIFFERENT SPEEDS*

SHEET THICKNESS (IN.)	TIMING SCHEDULE CYCLES		WELDING SPEED (IN./MIN)
	On	Off	
0.031	3	3	48
	2	1	96
0.039	3	3	48
	2	1	96
0.049	4	4	36
	2	1	72
0.078	6	6	24
	4	4	48
0.109	6	6	24
	5	4	48
0.125	6	6	24
	6	2	48

*_Welding Handbook_ (1942 ed.).

TABLE 12–13

SPOT-PER-INCH VALUES FOR SEAM WELDING DIFFERENT THICKNESSES OF STOCK*

Sheet Thickness (In.)	*Spots per In.*
0.031	12–14
0.039	12–14
0.049	12–14
0.062	11–13
0.078	10–12
0.109	9–11
0.125	8–10

*_Welding Handbook_ (1942 ed.).

Various types of circular electrodes for different joints are shown in Fig. 12–30.

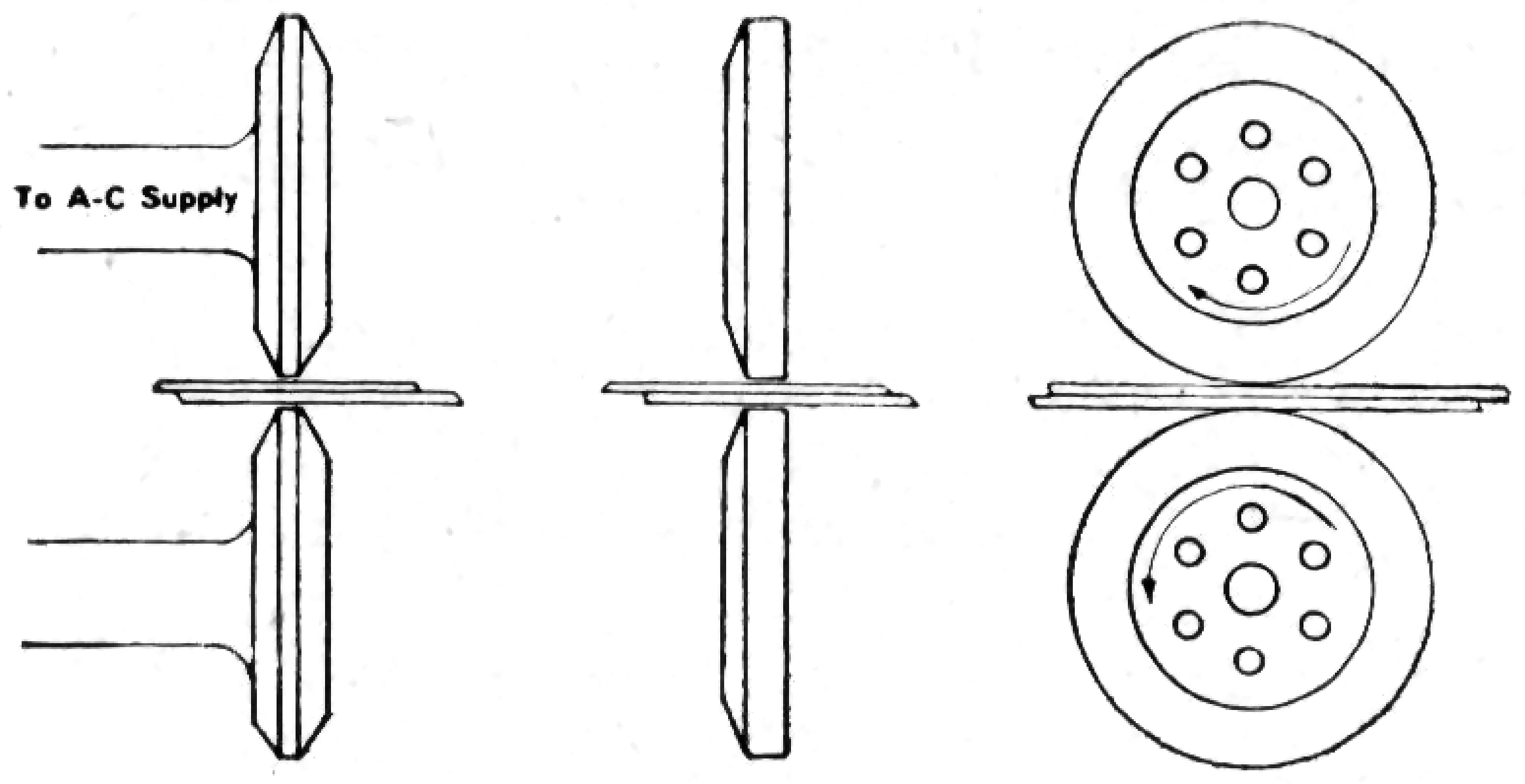
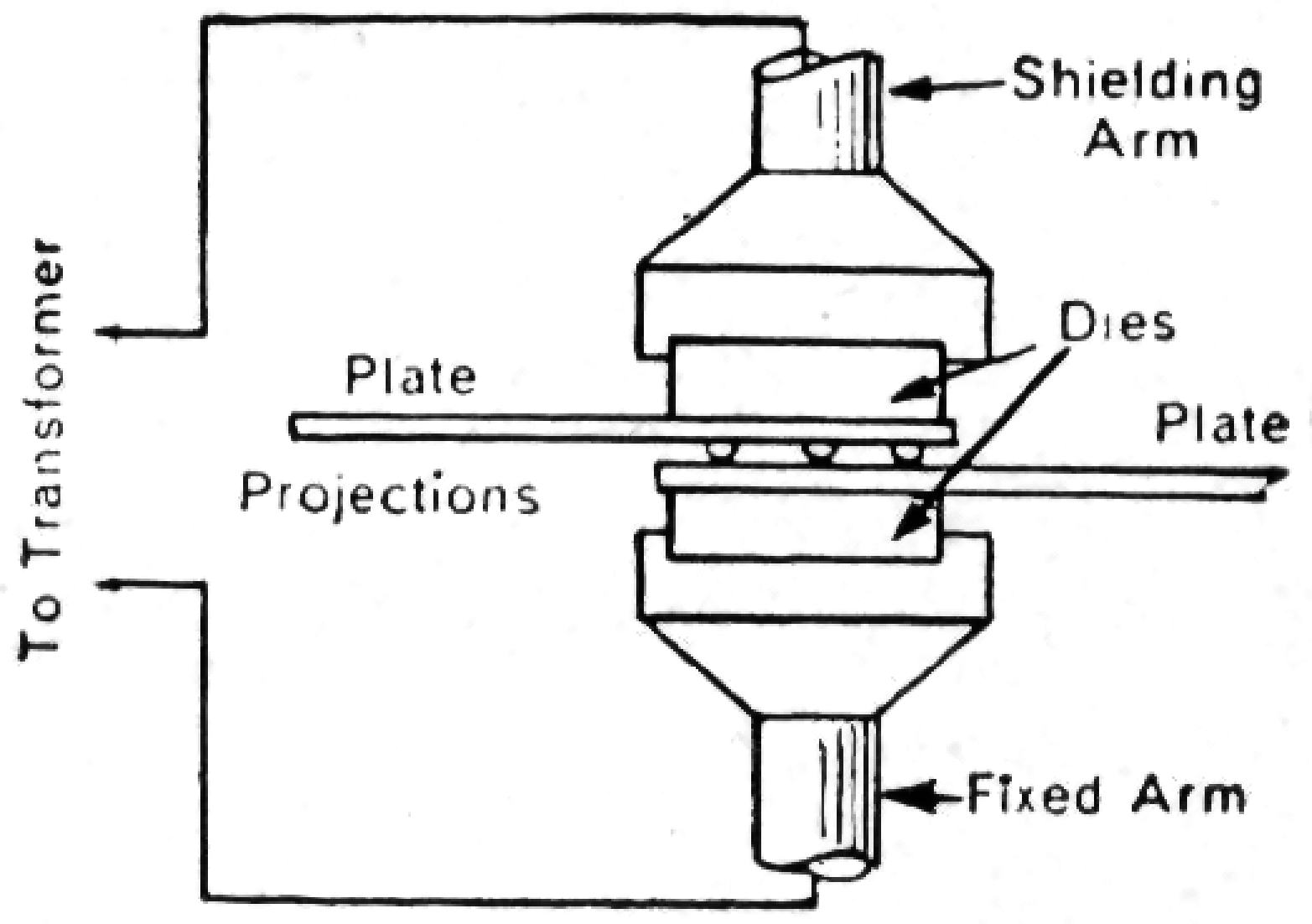


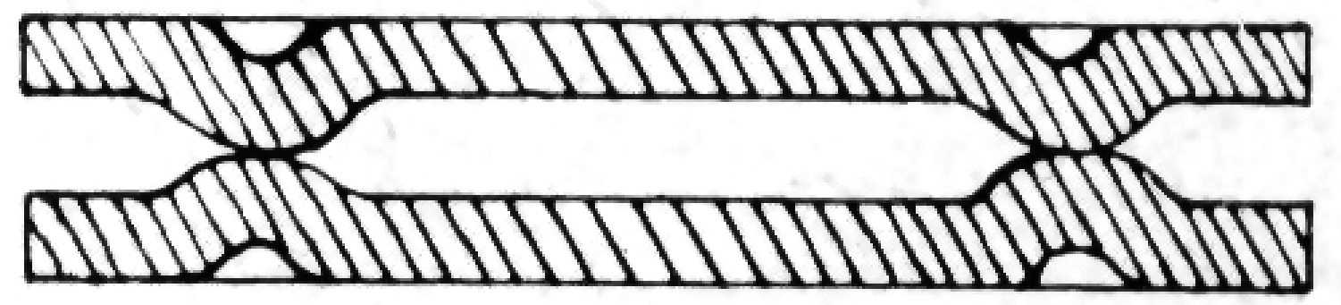
FIG. 12–30. Types of circular electrodes for seam welding.

Seam welding produces permanently tight and neat joints and reduces weight by utilizing smaller overlap than is used for bolted or riveted joints. It may also be used to weld metals varying in thickness from 0.003 to 0.187 in. With special equipment, metal up to 0.375 in. may be seam welded, and several seams may be welded simultaneously.

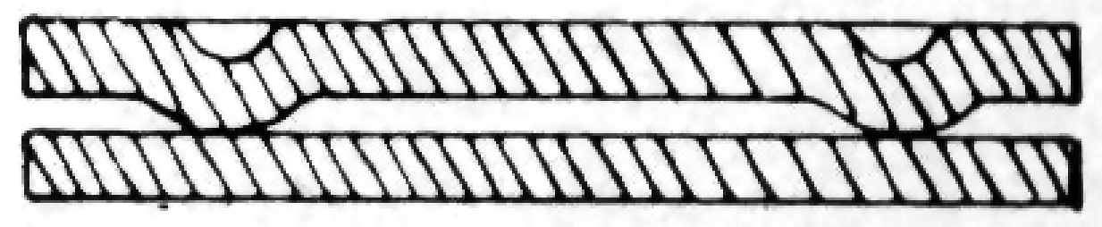
12–44. Projection Welding. Projection welding is another modified form of spot welding and is applied to projections or embossments, produced on one or more sheets in predetermined numbers and locations as required by the strength needed and by other considerations. A diagram indicating the basic principle involved is shown in Fig. 12–31.



Principle of Projection Welding



Cross-Section Showing Projections in Both Pieces Welded



Cross-Section Showing Projections in One Piece Only

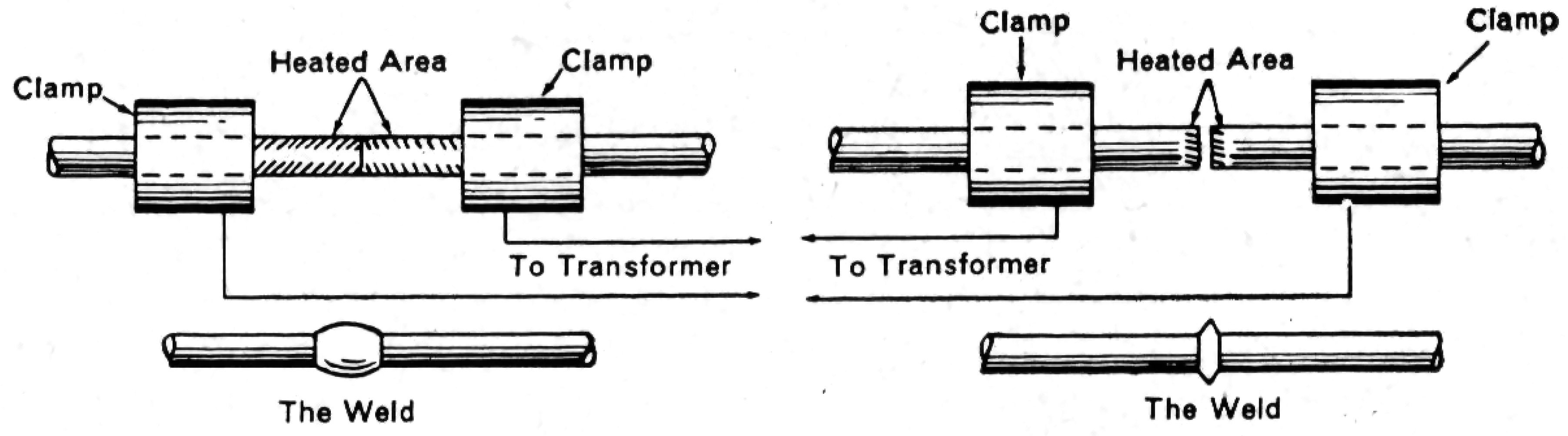
FIG. 12–31. Projection welding.

The assembled parts are placed between electrodes attached to platens fitting over the entire surface. These apply pressure to flatten the sheets and make simultaneous welds at each projecting surface or projection.

The advantages of this form of welding are: (1) a large number of projections are spot welded with one impulse or current flow; (2) flat and curved surfaces may be welded easily; (3) electrode life is extended by the decreased frequency of dressing; and (4) no other form of spot welding has so high a production rate.

Certain conditions inherent in the projection process limit its application somewhat. For instance, the metals must be ductile so that the projection can be raised, and they must be sufficiently strong so as not to collapse during the welding period. Copper and copper-rich brasses (red brass) are not considered weldable, while aluminum is weldable only to a limited extent. Metals coated with metallic coatings such as galvanized iron, tin, and terne (tin-lead alloy) plate are successfully welded. Combinations of certain dissimilar metals may also be welded.

12–45. Butt-Flash Welding. Push-butt welding is a form of resistance welding consummated between abutting edges or ends of sheets and bars, heated to welding temperature by resistance at the juncture, and held by the pressure applied by various mechanical devices, such as cams, springs, or levers.



(a) Principle of Butt Welding

(b) Principle of Flash Welding

FIG. 12–32. Elements of push-butt and flash-butt welding techniques.

Flash-butt welding is similar to the push-butt method in that the parts are securely clamped between suitable electrodes in a machine, wherein one set slides toward a fixed or stationary set. In the push-butt method, pressure is applied as soon as the parts are clamped, and the current is passed through the movable electrode to the work.

In flash-butt welding the current is applied *after* the parts are clamped and *before* the surfaces of the metals make actual contact. As the machine is set in motion and the parts approach closer together, the current arcs or flashes vigorously across the gap and heats the metals which, at the proper time, are pushed together to form a slight upset or increase in thickness through the weld section. A thin, ragged line of metal forced out of the weld is subsequently ground off. When sufficient heat and pressure have been applied to make the weld, the current is shut off automatically.

Fig. 12–32 shows diagrammatically the elements of push-butt and flash-butt welding techniques.

Flash-butt welding machines range in electrical power rating from ⅛ kva to 10,000 kva and may be used for welding various types of metals ranging from 0.0015 to a maximum of 500 sq in. in area.

12–46. Welding Currents and Voltages. As shown by Table 12–14, the lowest current value necessary to maintain a flash is 2,000 amp per sq in. with a maximum value of 25,000 amp for flashing metals up to ⅛ in. in thickness. Above this thickness, correspondingly lower currents are used to permit longer heating time and thus provide a wider plastic range for the upsets. The voltages range from ½ v to 5 v for butt welding, and from ¾ v to 20 v for flash welding. The upsetting pressures range from 2,500 to 8,000 psi for push-butt to from 5,000 to 25,000 psi for flash-butt welding.

TABLE 12–14

WELDING CURRENTS (AMP/SQ IN.) AND FLASHING SPEEDS FOR STEEL*

Thickness	Min. Current (Amp)	Max. Current (Amp)	Max. Time (Sec)	Min. Time (Sec)
18 gauge	2,000	6,500	7	3.2
1/16 in.	2,000	7,000	9	3
3/32 in.	2,000	10,000	9	2.5
⅛ in.	2,600	25,000	10	1.1
5/32 in.	2,600	23,500	10	1.6
3/16 in.	2,600	22,000	12	2.3
¼ in.	2,800	20,000	18	4.7
⅜ in.	3,000	18,000	24	8
½ in.	3,000	18,000	26	11
¾ in.	3,500	17,000	60	25
1 in.	3,500	17,000	90	40

* *Welding Handbook* (1939 ed.).

12–47. Weldable Metals. All commercially useful metals within the economical and practical capacity of the machine (except gray cast-iron) may be successfully welded by the butt-flash processes either to similar or to dissimilar metals. However, metals such as lead, zinc, tin, antimony, and bismuth and alloys in which these elements comprise the major constituents cannot be welded, because, among other reasons, they possess insufficient strength, volatilize too swiftly, or form refractory oxides which are not readily removed.

QUESTIONS AND PROBLEMS

1. Show by means of equations the complete combustion of acetylene and oxygen as produced for welding.
2. Show by means of equations the basic principle of the thermit process.

3. Give the chemical symbol for the oxide formed when steel is cut with oxygen.
4. Describe the method whereby acetylene is stored safely in tanks at high pressures.
5. Calculate the amount of oxygen theoretically required to oxidize one pound of iron.
6. List the principal functions of coatings on steel electrodes. Do the same for aluminum and stainless steel electrodes.
7. What conditions cause the voltage and amperage to be changed?
8. Why is copper used for gas welding tips?
9. Compare the weldability of a steel to its hardenability.
10. Name four nonpressure or fusion welding processes.
11. Name four resistance or pressure welding processes.
12. Is the thermit welding process applicable to the welding of nonferrous metals and alloys?
13. Are weldable metals also cuttable with oxygen?
14. Discuss the transfer of metal in metallic arc welding in atmospheric air and under shielded arc conditions.
15. Under what conditions may a high-carbon steel plate be cut with oxygen?
16. Does the high affinity of Al and Cu for O_2 indicate that these metals may be cut readily with oxygen? Explain.
17. Give the basic heat formula for resistance welding.
18. Compare spot, flash, butt, projection, and seam welding as to weldable metals and size.
19. It is not recommended that electrolytic copper be welded with the oxy-acetylene or oxyhydrogen processes. Why?
20. What is the basic principle of the atomic-hydrogen process?
21. Summarize the influence of welding on the structure and properties of steel and cast-iron.
22. List the advantages and disadvantages of the submerged arc process as compared to arc welding.
23. Explain the basic principle of the electric arc process of welding.
24. Explain "straight" and "reversed" polarity.
25. What condition is a prime requisite in the formation and maintenance of an arc between electrodes?
26. What conditions cause magnetic blow?
27. Materials of what type are used for electrode coatings?
28. In what respects is the rate of cooling subsequent to welding important?
29. Draw a symbol to indicate a modified U-butt joint with a ⅛-in. bead; a ⅜-in. fillet, 6 in. long, placed on 18-in. centers. Explain their significance.
30. Define "root," "heel," "throat," "undercut," and "overlap."
31. List the basic design and metallurgical factors involved in the economical production of weldments.
32. Calculate the strength in shear of two ¼-in. fillet welds, 72 in. long, in a lap joint.
33. Calculate the total length of a ⅜-in. fillet in two wide plates required to carry a total load of 120,000 lb.

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CHAPTER 13

BRAZING AND BRAZING ALLOYS

Brazing is a process whereby a strong bond is effected between metals by means of a relatively low melting alloy. It is being increasingly employed for a wide diversity of applications. Although popularly known as *bronze welding*, brazing is not strictly a welding process, since the base metal is not fused to the alloy. The process is, in some aspects, comparable to coating steel sheets with molten zinc to form galvanized sheets or soldering with a lead-tin solder.

The heating of the parts may be done in a furnace, with a blow torch, or in a forge; or the assembly may be submerged in a molten salt solution, a method called *dip brazing*. The brazing alloy may also constitute an electrode so that the process can be accomplished with an electric arc welding generator or transformer. A recent method consists of drawing an arc between two carbon electrodes and thereby heating by radiation both the base and the rod, which is manipulated as in oxyacetylene welding. The electrical induction method of heating, having the advantages of rapid and localized heating, is also widely used.

Originally the term "brazing" applied only to the joining of metals with copper alloys. The term now includes making joints with alloys containing silver, gold, cadmium, and nickel, as well as with pure copper. The silver- and gold-bearing alloys are applied in the same manner as the copper alloys. Brazing with pure copper is usually done by wrapping a copper wire of small diameter around the joint or by inserting it in the joint, in either wire or sheet form, and then heating the joint above the melting temperature of the copper, which flows by capillarity and gravity into the joint. No flux will be needed if the heating is done in an atmosphere devoid of excess oxygen such as may be obtained by the partial combustion of natural gas, coke oven gas, butane, or propane. An atmosphere obtained by the dissociation of ammonia (75 per cent H_2, 25 per cent N_2) is excellent for copper brazing. Substantial savings in machining costs are effected when simple punch press blanks are assembled and fabricated into useful parts by this method.

Brazing with copper alloys, as a method of producing strong and tight joints in metals, is adapted to both ferrous and nonferrous materials provided they possess a higher melting point than the alloy. Furthermore, it is extensively used for building up worn surfaces, reclaiming cracked steam cylinders, and repairing broken machinery parts, as well as for making fusion welds in brasses and bronzes. It is also the only practical and satisfactory method of effecting repairs in malleable iron castings, since it can be done at temperatures which cause no change in the structure of the metal. In general it is true that cast-iron parts are repaired as often by bronze welding as by fusion welding.

The value of bronze welding as a repair method in which the base metal is not fused or highly heated, as in fusion welding, lies in the fact that a strong and satisfactory bond can be obtained in cast-iron, for instance, at a temperature of 1400 to 1600F, whereas in fusion welding it must be heated to a temperature of from 2300 to 2600F, depending on the analysis. Because of this, internal stresses are reduced and cracking attributable to this cause is avoided. Preheating is also kept to a minimum or rendered unnecessary, and a considerable saving in time and labor is generally effected.

Success in producing a satisfactory bronze-welded joint can be achieved largely by giving attention to (1) the proper temperature of the base metal, (2) the proper temperature of the brazing alloy, (3) the cleanliness of the base metal, (4) the characteristics of the heating medium, (5) the proper fitting of the joints, and (6) the use of a suitable flux.

If the temperature of the base metal is too low, the alloy does not flow; if too high, it accumulates in small globules. Brazing is most successfully done when the alloy flows freely to cover, or *tin*, the metal in the manner of water spreading over a clean surface. This tinning is facilitated when the surfaces are maintained chemically clean by means of a flux which removes the oxides and prevents further oxidation of the hot surface. The most common flux for this purpose is dehydrated borax, to which boric acid is added.

A development recently reported in conjunction with the use of oxyacetylene for bronze welding provides for the bubbling of the acetylene through a dispenser containing a liquid flux. The flux in vapor form is picked up by the gas and carried through the hose and blowpipe to the flame where it produces the fluxing effect upon the metals.

To avoid porosity and loss of strength, it is important that copper alloys are not overheated, since many contain appreciable amounts of zinc, which volatilizes at a temperature only slightly higher than its melting point. The addition of silicon and tin to bronze welding rods reduces the fuming and oxidation of the zinc.

Brazing alloys are generally grouped on the basis of their melting point and, consequently, their application, since the alloy must melt at a lower temperature than the base metals. The silver-bearing alloys have the lowest melting point of any of the high temperature or brazing alloys with a melting point range from 1175 to 1600F. The melting point of the copper alloys varies between 1625 and 2250F.

The silver brazing alloys are extensively used in the electrical industry for joints in rotors, for switchboard bus-bars, and for connections and joints in wire. They are also used to effect strong, tight joints in copper tubing for oil lines, refrigerator parts, etc. Although more expensive than the copper-zinc and copper-tin alloys, the silver alloys require a lower working temperature and considerably less metal in a joint, and are easier to handle. The highest strength is obtained with a space tolerance in a sleeve type joint, shown in Fig. 13–1, of from 0.001 to 0.003 in. If the space is greater than 0.003 in. the strength of the joint is reduced.

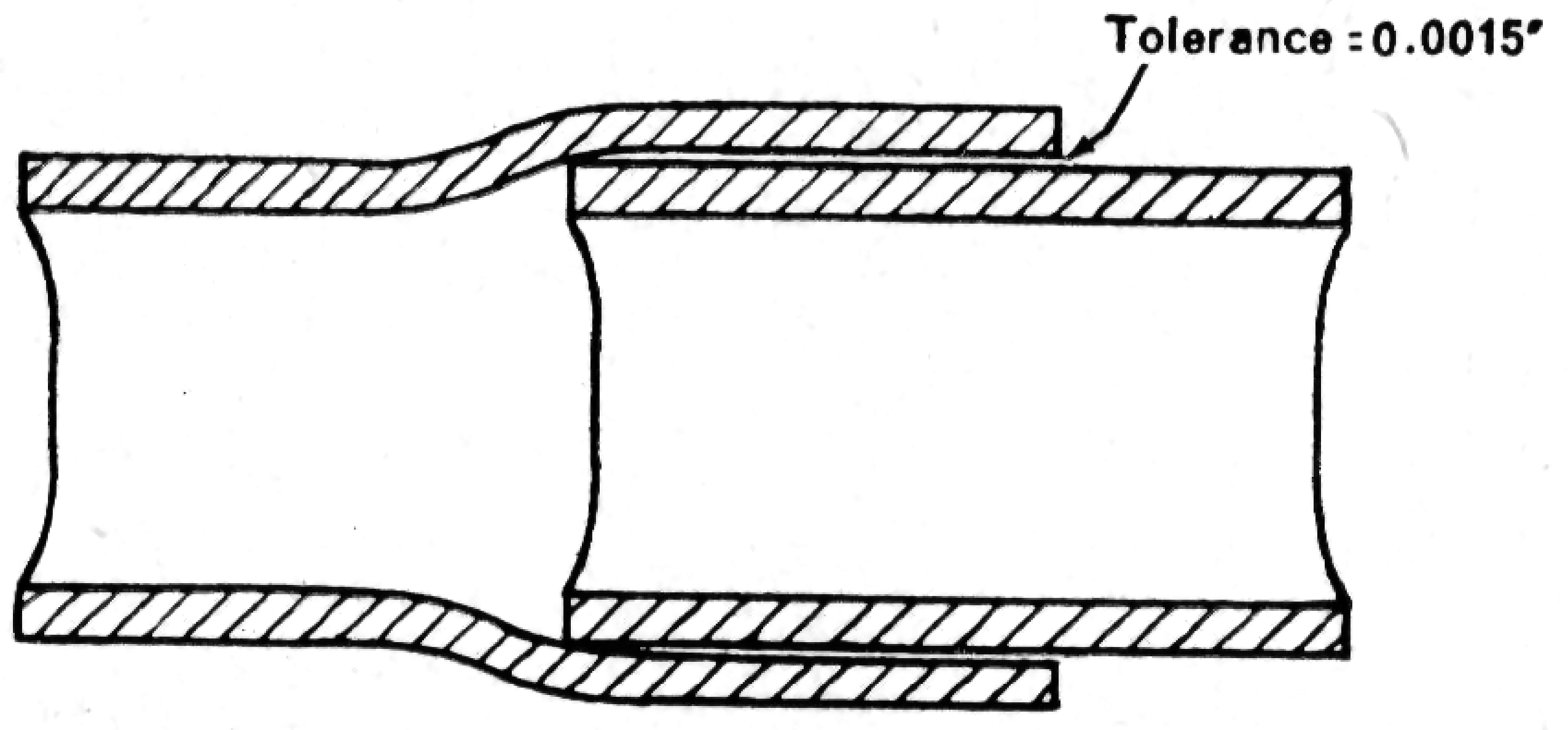

FIG. 13–1. Sleeve type of joint suitable for silver soldering with recommended tolerances.

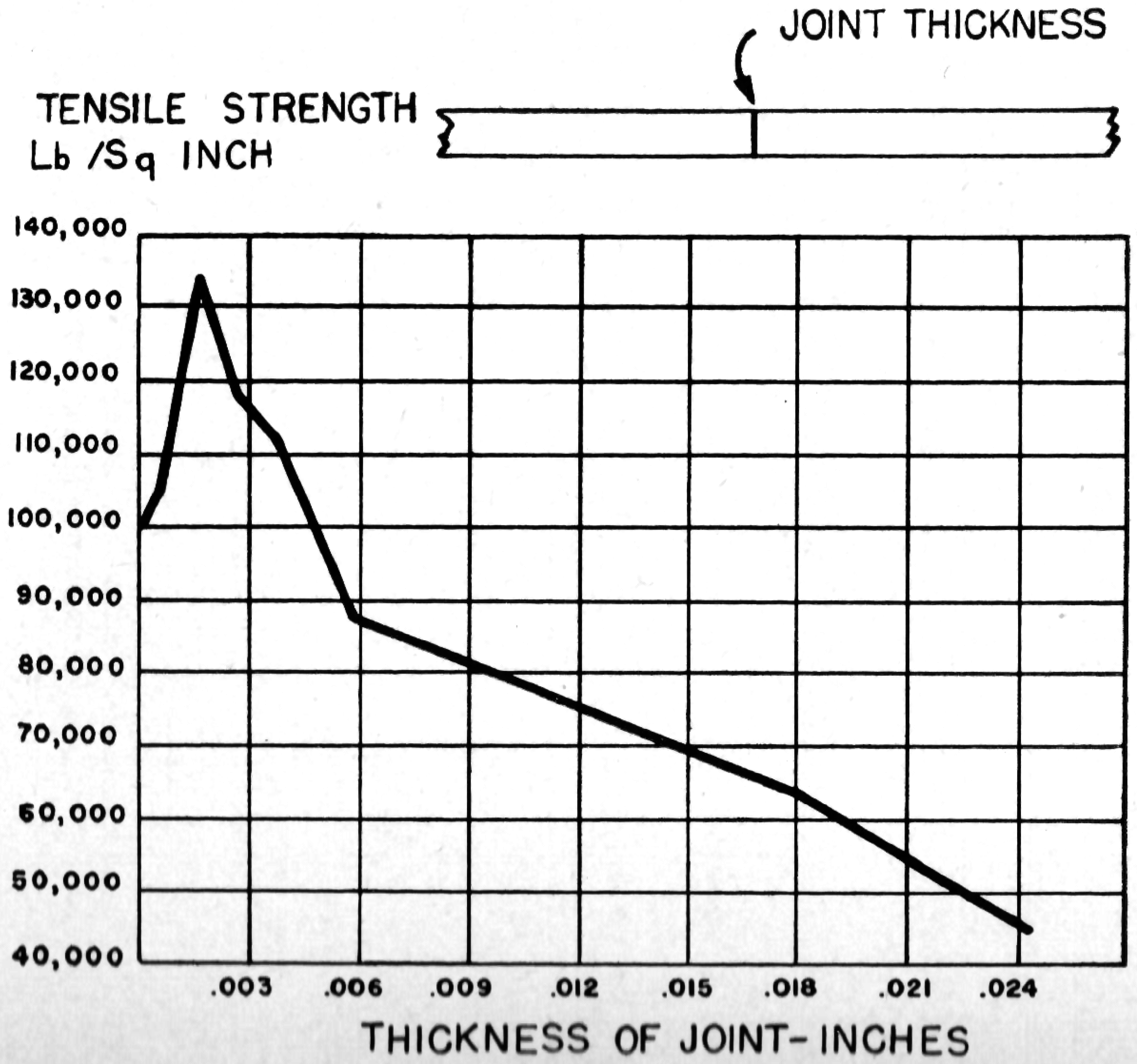

CHART BASED ON BUTT JOINTS–STAINLESS STEEL TO STAINLESS STEEL

FIG. 13–2. Relation of joint thickness to tensile strength.

TABLE 13–1

Representative Copper-Alloy Welding Rods

Alloy No.	Composition (Per Cent) Zinc	Tin	Manganese	Copper	Melt. Point (F)	Remarks: Color, Name, and Use
1....	38–43	0.50–1.50	....	Remainder	1625	Strong yellow bronze for general oxyacetylene welds on steel, cast-iron, copper, brass, bronze, and nickel alloys. Tobin bronze. Strength of approximately 50,000 psi in tension. Distinctive yellow color.
2....	38–43	0–1.5	0.05–0.75	Remainder	1600	Manganese bronze, quite similar to above except it is harder and more wear resisting than the Tobin bronze. Yellow bronze.
3....	.....	Silicon 3–4	0.75–1.25	Remainder	1860	Silicon bronze, Everdur. High strength of approximately 50,000 psi. Applicable by oxyacetylene torch to Everdur, copper, brass, bronze, nickel alloys and by the electric arc to Everdur, copper, bronze, and nickel. Pale red, characteristic bronze.
4....	.....	Tin 2–10	Phosphorus 0.03–0.40	Remainder	1950–1830	The familiar phosphor bronze. Good strength, 40,000 psi, excellent wear resistance for higher tin and phosphor proportions. More frequently applied by means of the metallic or long carbon arc. Applicable to copper, bronze, brass, steel, and nickel alloys. Copper-red to characteristic bronze color.
5....	23–27	Nickel 15–19	Manganese 0.05–0.15	Remainder	1930	Wrought nickel-silver. Nickel white color. Moderate strength 40,000 psi. Applicable only by oxyacetylene or carbon arc torches. Used principally in welding similar base metals.
6....	.....	Nickel 29–31	0.05–0.15	Remainder	2235	Cupro-nickel 70:30. Nickel white color. Good strength, 50,000 psi. Applicable to white metals by oxyacetylene torch or metallic arc. Covered electrode necessary for latter.
7....	.....	....	Phosphorus 0.03–0.09	Remainder	1980	Deoxidized copper. Used principally for welding copper by means of the oxyacetylene torch. 28,000 psi. Copper-red color.

Fig. 13–2 shows the tensile strength–tolerance relationship in square butt joints between stainless steel plates.

The composition of a representative group of copper-alloy welding rods is given in Table 13–1. The ASTM specifications for standard alloys are given in Table 13–2, and special silver solders are given in Table 13–3.

TABLE 13–2

Composition and Properties of Standard Brazing Alloys

Grade No.	Silver (Per Cent)	Copper (Per Cent)	Zinc (Per Cent)	Cadmium (Per Cent)	Impurities (Max. Per Cent)	Melt. Point (F)	Flow Point (F)	Color
1...	10	52	38	*	0.15	1510	1600	Yellow
2...	20	45	35	*	0.15	1430	1500	Yellow
3...	20	45	30	5	0.15	1430	1500	Yellow
4...	45	30	25	Nil	0.15	1250	1370	Nearly white
5	50	34	16	Nil	0.15	1280	1425	Nearly white
6	65	20	15	Nil	0.15	1280	1325	White
7	70	20	10	Nil	0.15	1335	1390	White
8...	80	16	4	Nil	0.15	1360	1460	White

*An addition, not to exceed 0.50 per cent of cadmium, to assist in fabricating Grade Nos. 1 and 2 shall not be considered as a harmful impurity.

TABLE 13–3

Special Silver Solders

Grade No.	Silver (Per Cent)	Copper (Per Cent)	Zinc (Per Cent)	Cadmium (Per Cent)	Lead (Per Cent)	Phos.	Melt. Point (F)	Flow Point (F)
1....	5.00	...	...	Remainder	...	...	640	740
2....	5.00	...	16.60	78.40	...	...	480	600
3....	5.50	...	...	...	Remainder	...	579	715
4*...	2.50	0.25	...	...	97.25	...	568	668
5†...	50.00	15.50	16.50	18.00	...	...	1160	1175
6‡...	15.00	80.00	...	...	...	5	1190	1300

**Proprietary Alloy*, Westinghouse Electric and Manufacturing Company.
†*Proprietary Alloy*, "Easy-Flo," Handy and Harman.
‡*Proprietary Alloy*, "Sil-Fos," Handy and Harman.

Solder Nos. 1 to 4, inclusive, are used where strength is not an important factor; but their higher melting range insures a greater margin of safety against failure at slightly elevated temperatures. In general, their other physical properties are more comparable to the standard soft solders. Solder No. 5 has the characteristics of the standard silver solders, and strong joints can be made in nonferrous and ferrous metals and alloys, including stainless steel. The advantages of this solder are its low flow point and the strength of joint.

QUESTIONS AND PROBLEMS

1. Compare the shear strength of bronze-welded sleeve type joints with ⅛-in. and 1/64-in. clearance.
2. What are the functions of fluxes in bronze welding?
3. Under what conditions may brazing be done without using flux?
4. List the advantages of bronze welding.
5. How are brazing alloys generally classified?

6. May some parts fabricated by brazing be reheated for heat-treating?
7. Name six brazing alloys.
8. In what respects do bronze welding and fusion welding differ?
9. Why should brazing alloys containing phosphorus not be used on ferrous metals?

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CHAPTER 14

PLASTICS MATERIALS, PROCESSES, AND USES

14–1. Introduction. The past few years have witnessed the development and the rapid growth in production and application of a series of engineering and industrial materials designated as plastics. The name, which could be applicable to any substance capable of being plastically formed, is today exclusively identified with products that are derived from natural or synthetic resins and are plastically molded, cast, or extruded in a semiliquid state to various forms, which subsequently retain their approximate shape in service.

The modern plastics industry traces its actual beginning to Dr. Leo Baekeland's discovery, in 1909, of wholly synthetic resin by reacting phenol and formaldehyde and producing an almost insoluble and infusible material. Spurred by a constantly growing demand that has grown out of expanding uses, research has since produced a large number of new plastics with a wide range of characteristics and properties so that today almost every industry makes extensive use of them, either as finished products or as complementary parts of units whose major components are metal, wood, fabrics, leather, etc.

Although used for some parts formerly produced of metal, plastics are not comparable to the various metals in strength, ductility, hardness, or adaptability for low or high temperature; in addition, they do not have the wide range of mechanical properties developed in metals by heat treatment or mechanical work. Their extraordinary popularity is due to a wide variety of reasons; some of them are: the relative ease and economy with which they are produced, their suitability for mass production processes, their durability and light weight, their availability in a large variety of pleasing colors, their excellent surface finish, and their high electrical resistance. Plastics are widely used for household appliances and decorative trimmings, as well as in the radio, automotive, electrical, and aircraft industries for protective surface coatings or for parts not subject to high stresses or wide variations in temperatures.

There are many instances where plastics may well be substituted for metal parts. Industry will best be served, however, when the engineer or designer determines the specific sphere in which the desirable characteristics of plastics and metals, as well as all other materials, are fully realized. Materials of widely differing properties and characteristics supplement, rather than displace, each other. And the greatest good results when they are skillfully combined to take the fullest advantage of their basic characteristics.

For example, metallic inserts—such as screws, bolts, or other fasteners—are commonly used in plastic bases, in which they are firmly held. Metal is also electrodeposited into molded grooves on commutator surfaces, and design plates are made with various metals deposited on a plastic background. There are many other applications in which both metals and plastics are combined.

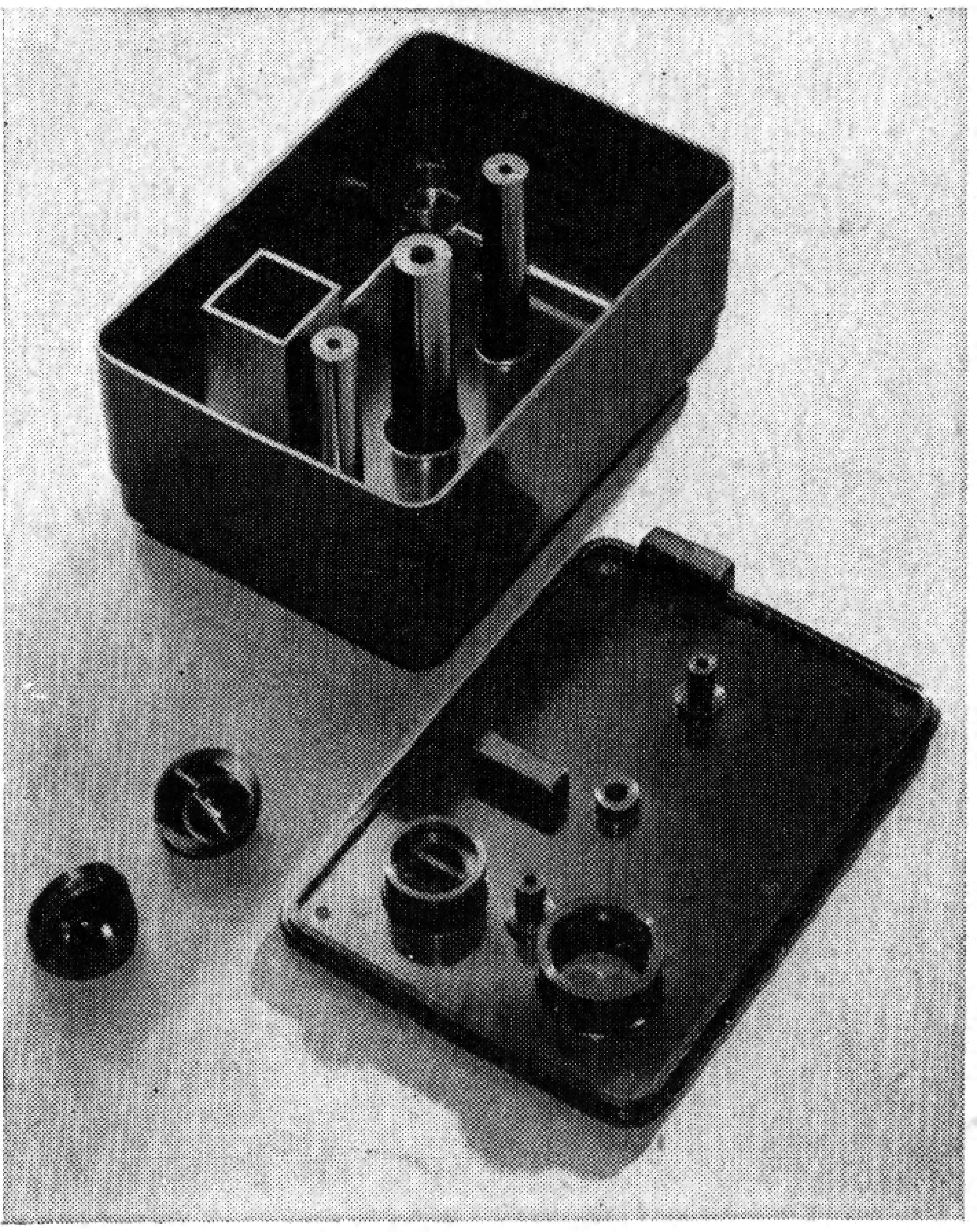

FIG. 14–1. Plastically molded vaporizer unit. Main body measures 7¾ in. long, 5⅜ in. wide, and 3¾ in. deep. (Courtesy of Durez Plastics and Chemical Co., North Tonawanda, New York.)

14–2. Classifications of Plastics. The term plastic implies a synthetic organic material consisting of a binder derived from a resinous or cellulosic source. During its production it is capable of being either plastically molded or cast from a liquid condition. In general, plastics are classified on the basis of their degree of hardness and thermal stability and are known as thermosetting and thermoplastic. Thermosetting resins, of which the phenolics and the ureas are examples, are polymerized under the application of heat and pressure and retain their form and hardness within a relatively wide temperature range. They cannot be remelted or remolded. A number of thermosetting plastic parts are shown in Figs. 14–1, 2, and 3. In contrast to the thermosetting materials, thermoplastic compounds, represented by the acetates and vinyls, are tough and fairly plastic, soften with heat, and may be remelted and remolded.

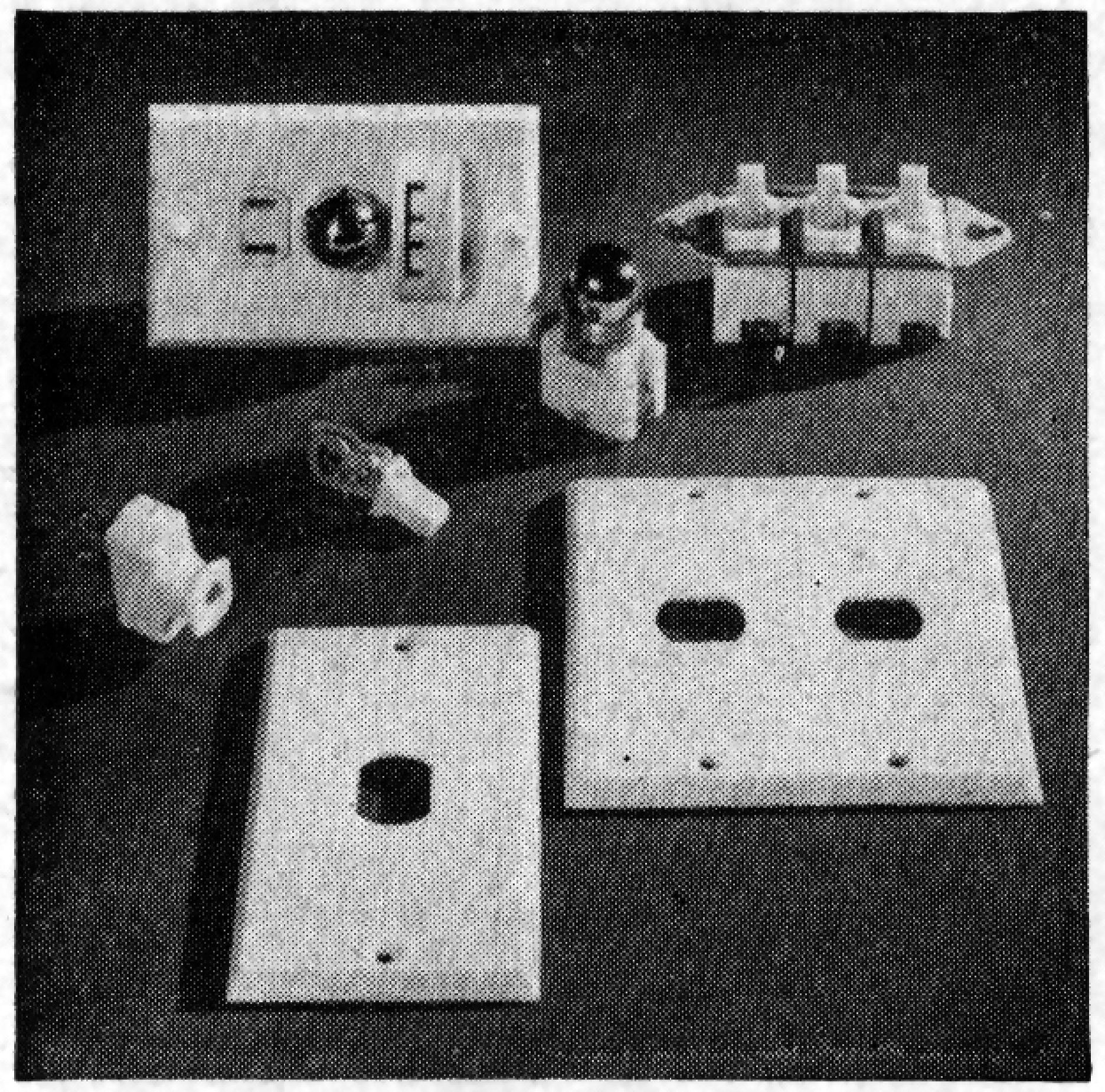

FIG. 14–2. Plastically molded electric wall switches and cover plates. (Courtesy of Durez Plastics and Chemical Co., North Tonawanda, New York.)

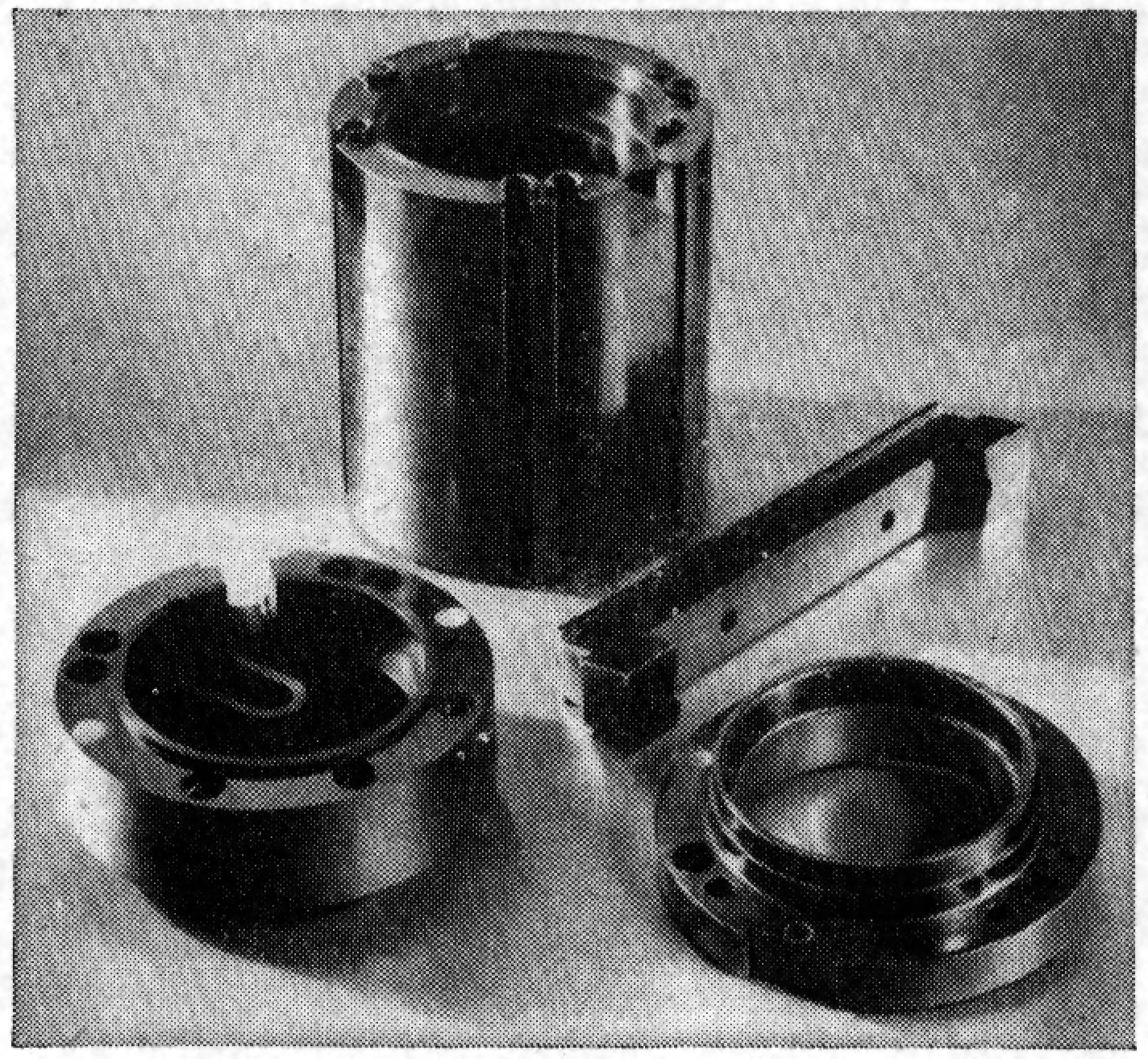

FIG. 14–3. Plastic molded parts for high-frequency induction heating unit for heat-treating steel parts. (Courtesy of Durez Plastics and Chemicals Co., North Tonawanda, New York.)

Table 14–1 constitutes the synthetic and natural resins from which modern plastics derive.

TABLE 14–1

CLASSIFICATION OF PLASTICS RESINS

Synthetic Compounds	Cellulose Derivatives	Natural Resins
Thermosetting plastics	Cellulose acetate	Asphalt
Phenol formaldehyde	Cellulose nitrate	Pitch
Phenolic resins	Ethyl cellulose	Amber
Soybean phenolic	Lignin	Shellac
Urea aldehydes	Casein	Rosin
Melamine formaldehyde	Cellulose acetate butyrate	Bitumen
Aniline formaldehyde		
Thermoplastics		
Vinyl ester resins		
Vinyl chloride acetate copolymer		
Vinyl aldehyde resin		
Vinylidene chloride		
Acrylic resins		
Polystyrene		
Polyvinyl alcohol		
Polymethyl methacrylate		

14–3. Molding Materials. Plastics are composed of the resinous substance, which is the binder, in combination with dyes, pigments, lubricants, and common fillers. These fillers play an important part in influencing the mechanical, chemical, and electrical properties of the plastics. They also reduce the cost of the molded articles by replacing a part of the more expensive chemical materials with the cheaper fillers. The addition of these fillers also effects significant changes in such properties as resistance to moisture, heat, shock, and abrasion, according to the type of filler used. The fillers also influence the molding characteristics and the machinability.

The fillers most commonly used are organic substances consisting of wood flour, cotton flock, fabric, and alpha cellulose fibers. In addition several inorganic substances are also used to provide such specific properties as good heat and moisture resistance, good insulation, high dielectric strength. a low shrinkage in molding, and a low coefficient of heat expansion. The most common inorganic fillers are mica, silica, and asbestos. These, however, usually cause poorer machinability, increase the specific gravity, and impair the molding characteristics.

14–4. Wood Flour. One of the most widely used fillers for phenolic plastics is wood flour. Because of its low cost, availability, low specific gravity, good moldability, good surface finish, and low heat conductivity, it is satisfactory for general-purpose plastics. Over one-half the bulk of many articles in the plastics industry consists of wood flour filler. The specific amount varies according to the type and quantity of the resin, coloring, plasticizer, and the other constituents. The influence of various amounts on the flexural and impact strength is shown in Table 14–2.

TABLE 14–2

INFLUENCE OF VARIOUS PERCENTAGES OF WOOD FLOUR ON THE FLEXURAL AND IMPACT STRENGTH OF PLASTICS*

Wood Flour (Per Cent)	Resin (Per Cent)	Flexural Strength, Psi	Impact Strength, Psi
80	10	16,000	0.75
75	15	14,000	0.70
70	20	12,000	0.65
60	30	10,000	0.60
50	40	9,000	0.40
45	45	8,000	0.35

*Simonds and Ellis, *Handbook of Plastics.*

The principal disadvantages of wood flour filler are a low heat resistance, only fair strength, and moisture absorption.

14–5. Cotton Filler. Cotton flock, or finely divided cotton fibers, and fabric materials produce considerably higher impact, tensile, and flexural strength in the thermosetting plastics than is obtainable with the use of wood flour. Although they are more expensive than the wood flour, their more desirable properties fully warrant their use. These fillers are obtainable in various grades from light cotton to heavy canvas. They are also available in fibers that are of uniform length, of controlled bulk, and are free from extraneous matter. Cotton filled phenolics may be buffed and polished, and may be molded into thin sections. Their moisture resistance equals that of wood flour filled materials. The fabric filled materials are difficult to mold, especially into complex shapes, have poor machinability, and have a markedly poorer surface finish than the cotton filled materials. The influence of various fillers on the mechanical and electrical properties of plastics is shown in Table 14–3.

TABLE 14–3

INFLUENCE OF FILLERS ON MECHANICAL AND ELECTRICAL PROPERTIES OF PHENOL FORMALDEHYDE PLASTICS

Properties	Wood Flour Filler	Mineral Filler	Fabric Filler
Specific gravity	1.25–1.52	1.59–2.09	1.37–1.40
Specific vol., cu in./lb	22.2–18.2	16.4–13.3	20.2–19.8
Tensile strength, psi	4,000–11,000	4,000–10,000	5,000–8,000
Compressive strength, psi	16,000–36,000	18,000–36,000	20,000–32,000
Flexural strength, psi	8,000–15,000	8,000–20,000	8,000–13,000
Impact strength, ft-lb per in. of ½ by ½ notched bar, Izod	0.15–0.25	0.13–0.72	0.8–4.8
Dielectric strength, short time, volts per mil, ⅛ in. thickness	300–500	250–400	150–450
Dielectric constant:			
60 cycles	5–12	5–20	5–10
1,000 cycles	4–8	4–20	4–6
1,000,000 cycles	4–8	4–20	4–6
Power factor:			
60 cycles	0.04–0.30	0.10–0.30	0.08–0.30
1,000 cycles	0.04–1.15	0.10–0.15	0.08–0.20
1,000,000 cycles	0.04–0.1	0.01–0.1	0.04–0.10
Water absorption, per cent in 24 hr	0.2–0.6	0.01–0.3	0.5–2.5

14–6. Plasticizers. As implied by their name, plasticizers are added to increase plasticity, to soften or otherwise make tough a brittle or inflexible material. Unless modified by plasticizers, many resins lack any toughness and become increasingly brittle with age. In order that only the desired degree of softness and toughness be obtained, and since plasticizers tend to reduce the tensile strength of thermosetting plastics, both the composition and concentration of the plasticizer must be carefully chosen. Plasticizers include ethylhexyl, tricresyl-phosphate, methyl, ethyl, butyl, and many other complex hydrocarbons. Selection is also made on the basis of good color stability, high ductility, and moisture resistance.

14–7. Lubricants. Lubricants are either applied to the molds directly or added to the plastics compound to facilitate molding and to aid in the quick removal of the parts from the mold. Wax, oils, fats, metallic soaps, oleates or stearate, and graphite are among the lubricants used.

Dyes and pigments may be added to plastics to change their natural color of amber or brown and to produce a variety of other shades to satisfy esthetic, psychological, or commercial appeals. Luminescent pigments are commonly applied to water-clear plastics to produce light effect in the absence of daylight.

14–8. Plastic Compounds. For a detailed discussion of the characteristic properties, processing, and applications of the vast number and variety of plastics manufactured, sources listed at the close of this chapter as well as the many articles which appear in periodicals must be consulted. In this chapter only a general description of the more outstanding plastic resins will be given.

14–9. Phenolics. Phenolic resins are compounded by reacting phenol (carbolic acid) with an aldehyde, most commonly formaldehyde. These constituents are cooked in steam-heated autoclaves to produce a viscous syrup. After cooling, this material is ground and mixed with a lubricant and other materials in various proportions for plastics molding. These resins are thermosetting and are produced by compression and injection molding, as described later. They can be compounded with fillers and reinforcing agents to provide a wide range of physical, chemical, and molding properties. They may also be produced without a filler, and are then transparent and have a white, amber, or other color. Since the lighter colors change to darker shades when exposed to the sun and other elements, phenolic compounds are generally mixed with pigments to produce a number of more stable colors such as black, brown, maroon, red, blue, and green. A variegated effect may also be obtained by a combination of these. The plastics are uniform in texture and gemlike in luster.

Phenolic resinous compounds produce the most widely used and best known of the all-purpose thermosetting plastics. They give the maximum economy for applications where no special physical or chemical properties are required. Where resistance to shock, moisture, electricity, and heat, as well as dielectric properties, are required, phenolics with canvas, asbestos, or mica fillers are available. These, however, are more difficult to mold, and therefore the filler and its concentration must be chosen with respect to its effect on both the desired properties and its moldability.

14–10. Cast Phenolics. Cast phenolic plastics are in the thermosetting group and are produced from resinous compounds prepared in a manner conforming to the same fundamental polymerization reaction as those used for molding. Combined with the requisite amount of formaldehyde and a catalyst, the phenol is liquefied and stirred vigorously until a mixture forms and is separated into two layers, consisting of the water of condensation and the resinoid. For the production of molding compounds, all the condensation is removed by vacuum; but in the preparation of resinoid for casting, the water content is controlled accurately. The resin, having a honey or syruplike consistency, is poured into lead molds, die-cast split molds, or plaster or glass molds; and these are then placed in furnaces and heated from 158 to 177F for from 3 to 7 days. Here the second stage of the polymerization takes place and the plastics are hardened and strengthened. When cool, they are polished or machined as required. Cast phenolics are furnished in sheets, bars, rods, tubes, and various other shapes and in a wide variety of translucent colors.

14–11. Urea Formaldehyde Plastics. With the exception of the molded phenolics, urea formaldehyde plastics are probably the most widely used. They possess physical properties similar to those of the general-purpose flour filled phenolics, and, aside from slightly higher mold pressure, they are molded in the same ways. They primarily appeal because they offer a wide selection of attractive colors, transmit light, may be produced with a translucency varying in optical density from their natural color to opaque whites, and are colorfast. They are resistant to alcohol, grease, oils, and common solvents. They are damaged quickly by strong acids and alkalies, and are not suitable for outdoor use where their exposure to moisture will cause warping, cracking, and increased brittleness. They may be used satisfactorily up to a temperature of about 175F and almost to 250F intermittently and for a short duration. Higher temperatures, however, cause injury and darken the colors.

Urea plastics are of the thermosetting group and therefore retain their shape and hardness at ordinary temperatures. Since they are tasteless, odorless, and nontoxic, they may be used in contact with food and are suitable for cups, tumblers, plates, and bottle closures. Some of their other uses are in buttons, door pulls, lamp reflectors, domelights for automobiles, switch plates, plugs, sockets, packaging for pens, watches, toilet articles, clock and radio cabinets, electric razor housings, and display cabinets.

Urea is present in, and recoverable from, farm manure but is produced synthetically by reacting ammonia and carbon dioxide under conditions which cause them to combine to form a solution of urea and water. When the water is removed, white crystals of urea remain.

The resins are produced by reacting urea with formaldehyde at a temperature of about 120F in the presence of a catalyst, such as sodium hydroxide, and a plasticizer. When mixed with dyes, fillers, and plasticizers, the viscous substance is cooled and ground to a size suitable for molding. The resin attains its final polymerization stage when molded under heat and pressure.

Because the ureas are used principally for their fine colors, only pure alpha cellulose with its natural whiteness is used as a filler, furnished in either a pulverized or flock form.

Urea molded plastics cost considerably more than the dark colored phenolics.

Mixtures of urea and formaldehyde are prepared as the impregnants of wood fabrics and paper in the production of laminated sheets of various thicknesses and strength. Wood laminations are widely used where solid wood was formerly used.

The various properties of the urea formaldehyde molding compounds are given in Table 14–4.

TABLE 14–4

PROPERTIES OF UREA MOLDING COMPOUNDS*

Forms available	Fine powder, granules
Molding qualities	Excellent
Molding temperature (F)	290–320
Molding pressure, psi	1,500–6,000
Colors	Unlimited, from natural colorless to black
Specific gravity	1.45 to 1.50
Tensile strength, psi	5,000–13,000
Compression strength, psi	24,000–35,000
Flexural strength, psi	10,000–15,000
Impact strength, ft lb per in. of notched ½ × ½ bar	0.28–0.32
Softening point	None
Cold flow	None
Upper temperature limit continuous (F)	180
Distortion (F)	None below 180
Burning rate	Chars, does not support combustion

*Courtesy of Plaskon Company, Inc.

14–12. Acrylics. Plastics produced from resins obtained by the polymerization of acrylic acid and its derivative methyl methacrylate constitute a group of thermoplastics of relatively recent development. They have a very considerable technical and commercial value, as well as a popular appeal and interest.

The resins are supplied in various degrees of fineness and in a soft or hard condition for either extrusion injection or compression molding, as described later, and also as sheets, rods, and tubes. The plastics are produced in highly polished metallic molds at a temperature of from 280 to 350F, depending on the type of compound. They possess a crystal clear, polished surface and are colorless. The addition of suitable dyes and pigments to the resin, however, makes possible a variety of beautiful colors and pastel shades.

To maintain their distinctive characteristic transparency no fillers or plasticizers are used. The materials are resistant to moisture, oils, dilute acids, alcohol, and alkalies. They are shatterproof, have excellent dielectric strength, and their specific gravity is 1.19 compared to 2.5 for glass. Their tensile strength varies from 5,000 to 12,000 psi and they have fair ductility when cold. Heated to between 200 and 300F, molded sheets may be bent to various shapes; and they may be filed, drilled, sawed, milled, or turned on a lathe. They are also colorfast.

Because of their high optical efficiency they are widely used in preference to glass where a high transparency and clearness of vision are required with shatterproof properties. When impaired by scratches or markings, transparency may be restored by buffing and repolishing on linen buffing wheels.

Some of the various applications of molded and cast acrylic plastics are aircraft cockpit and turret enclosures, side windows for airplanes, covers for dials and indicators, lenses and goggles, handles for toilet articles, and dentures. Cast acrylic plastics are produced by filling heated molds conforming to the desired shape with the syrupy monomeric (liquid acrylic resin) methyl methacrylate, previously mixed with a catalyst to produce subsequent hardening or polymerization.

Paper, cloth, or wood may also be impregnated with acrylic monomers to form strong and durable laminated sheets. These may be used for electrical insulation and for structures which require strength, light weight, and toughness.

14–13. Methyl Methacrylate. The best known of the methyl methacrylate resins are Lucite,* Crystalite,† and Plexiglass.†

The resins are also available for use as adhesives for wood, leather, metal, rubber, and similar materials. They produce a colorless, transparent bond and are unaffected by bacteria and fungi.

When dissolved in organic solvents, acrylic solutions are adaptable for the impregnation of wood, wallboard, cloth, cork, paper, and electrical coils. When baked, they become polymerized and form the resins.

Enamels containing acrylic resins may also be painted or sprayed on metals and fabrics to give a lustrous, hard finish.

14–14. Cellulose Nitrate. Plastics compounded of nitrated cellulose have been familiarly known as celluloid. They are the original plastics produced from synthetic materials. The resins are obtained when purified alpha cellulose is reacted with sulphuric and nitric acids in a mixer or nitrator provided with a mechanical agitator.

When thoroughly washed to remove all traces of the acids, the doughy cellulose nitrate mass is soaked with alcohol, colloided in a mixer with a plasticizer, usually camphor, and strained in hydraulic pressure filters. The mass is then kneaded on polished and heated rolls, at which time pigments are added and the alcohol is evaporated. The rolled sheets are compressed with the aid of heat into solid blocks and are baked to remove moisture and air bubbles and to produce a homogeneous mass. The blocks are later sliced into sheets of the required thickness, aged to remove the solvents, and given a polished surface by pressing between heated polished plates. Extruded forms, such as rods and tubes, are produced when the warm plastic mass is led directly into the extrusion press from the kneader. When the volatile solvents are removed, the resin hardens and is ground for molding.

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*E. I. Du Pont de Nemours and Company.

†Rohm and Haas Company.

Cellulose nitrate or pyroxylin plastics are thermoplastic and, when heated to between 160 and 250F, they may be molded, extruded, or pressed into bulbs or other shapes by deep drawing or by being blown with compressed air.

In contrast to the phenolics and ureas, cellulose nitrates are not adapted in the granular form for compression molding because the particles do not become sufficiently coherent and may be disintegrated easily. The molding therefore consists of pressing preformed and precut shapes of required volumes in heated molds at pressures from 2,000 to 5,000 psi. They are unsuited to injection molding because of their sensitivity to the higher molding temperatures required.

These plastics are naturally transparent and may be obtained colorless. Because they discolor with age, they are commonly produced in a variety of colors, both solid and patterned, and in translucent, opaque, and pearl effects.

They are easy to work, have excellent water resistance, are tough and dimensionally stable, and for many uses are the cheapest. Their chief defect is inflammability. They should not be used at temperatures above 320F, as they burn swiftly and liberate camphor vapors.

Nitrocellulose resins are also available as lacquers and emulsions, which may be sprayed on metallic and other surfaces to any thickness and in any color.

The molded plastics may be drilled, turned, tapped, cemented together, and polished. Their principal properties are shown in Table 14–5.

14–15. Cellulose Acetate. Cellulose acetate thermoplastics are produced from a solid solution prepared by the reacting of pure alpha cellulose with acetic acid and acetic anhydride and sulphuric acid catalyser. Although of relatively recent development they have been widely substituted for the cellulose nitrate materials for service where the inflammability of the latter may cause fire hazards or where resistance to higher operating temperatures is required. Their use for 8 and 16 mm movie film is prescribed by law, although commercial films are made of cellulose nitrate material.

After bleaching and scrubbing to obtain pure cellulose, the cotton linters or (wood cellulose) are dissolved in the acids to produce a resin to which are added plasticizers, solvents, and dyes. These are thoroughly worked into the mass by rolling into sheets on heated rolls. After seasoning at high temperature to remove the solvents, the sheets either are ground into molding powders or are reheated and pressed together to form a block several inches thick, which is later sliced into sheets of the required thickness.

The cellulose acetate content of the most useful plastics varies from 60 to 80 per cent with the plasticizers blended to obtain the desired hardness, toughness, resiliency, elongation, and strength. In general, the mechanical properties are similar to those of the cellulose nitrate materials.

TABLE 14–5

VARIOUS PROPERTIES OF CELLULOSE NITRATE MOLDED PLASTICS

Specific gravity	1.35–1.60
Clarity	Transparent to opaque
Colors	Unlimited possibilities
Tensile strength, psi	5,000–10,000
Elongation, per cent	10–40
Compressive strength, psi	20,000–30,000
Impact strength ft/lb energy to break ½ × ½ in. bar	3–12 (Charpy)
Dielectric strength 60 cycles volts/mil	600–1,200
Effect of light	Yellows and decomposes; becomes brittle
Aging effect	Hardens
Effect of acids (weak)	Slight
Effect of acids (strong)	Decomposes
Effect of alkalies (weak)	Slight
Effect of alkalies (strong)	Decomposes
Effect of organic solvents	Soluble in acetone, amyl acetate, acetic acid, alcohol-ether mixtures.
Molding qualities	Good
Compression molding pressure, psi	2,000–5,000
Compression molding temperature (F)	185–250
Tendency to cold-flow	Slight

The principal differences are that the cellulose acetate products are suitable for both injection and compression molding. They may be molded with ease and at a faster rate than any others and, because of their high coefficient of expansion, they shrink tightly around inserts. They are also less inflammable. At low temperatures their toughness decreases rapidly and they soften when heated to about 150F. They remain unaffected by ordinary temperatures, have a low thermal conductivity and high dielectric and insulating properties, and are more satisfactory for low loss and high resistivity than the general-purpose phenolics. In moisture absorption, however, they compare very unfavorably, as they swell and consequently lack dimensional stability.

They are available in a wide variety of beautiful and brilliant lightfast colors including water white, mottled, onyx, tortoise shell, pearl, and an unlimited choice of translucent and opaque solid colors. They are produced in sheets, rods, tubes, foils, films, and lacquers for coatings. They may also be cemented together with a cement consisting of cellulose acetate dissolved in acetone. They are slightly resistant to weak acids and are unaffected by gasoline, benzol, toluol, mineral and vegetable oils, alcohol, and ether.

Their tensile strength varies inversely with the relative amount of plasticizers and ranges from 2,800 to 10,000 psi.

14–16. Cellulose Acetate Butyrate. By treating the cellulosic materials with butyric acid in addition to the acetic acid and acetic anhydride, a molding compound is obtained which is suitable for producing, through both injection and compression molding, a thermoplastic product with moisture and weather resistance (and hence dimensional stability) that are much superior to the cellulose acetate compounds. Cellulose acetate butyrate plastics contain a much smaller quantity of plasticizers, but include those which have a greater moisture resistance and provide a greater dimensional stability. Except for the advantages mentioned, the properties and applications of cellulose acetate butyrate plastics are similar to those of the other acetates.

14–17. Polystyrene. Polystyrene resins have been produced on a commercial scale only since 1937, although the production of these resins has been known for over a century. Polystyrene is derived from styrene, a clear liquid which results from the reaction of ethylene and benzene after cracking ethyl benzene under heat and pressure. After polymerization the liquid becomes a hard, tough, and colorless resin, which may be colored by adding dyes or pigments while kneading the mass on heated rolls. After cooling, the sheets are ground and furnished as powder for injection and extrusion molding.

Polystyrene molding powders are usually compounded without any plasticizers, which gives to these plastics exceptional dimensional stability and practically no moisture absorption. They are also characterized by crystal clarity, low inflammability, and high ultraviolet light transmission. They are available in all opaque colors and mottles; and they may be identified from other plastics by the clear resonant sound they make when struck or dropped on a hard surface.

Other outstanding characteristics are unusual dielectric strength, low specific gravity (1.07), and excellent resistance to alcohol, water, many acids, and alkalies.

14–18. Melamine Formaldehyde. These resins are compounded of formaldehyde and melamine, a product obtained from dicyanodiamide by the syntheses of nitrogen and calcium carbide. These plastics are of the thermosetting group and, in general appearance and molding characteristics, are similar to the filled urea formaldehyde compounds. They have slightly higher heat resistance and are molded at higher temperatures. They also are harder and more resistant to various chemicals than the ureas and have a low moisture absorption.

Alpha cellulose filled melamine formaldehyde compound is inherently colorless, lightfast, and translucent. By proper choice of dyes and pigments, it may be made available in an unlimited range of stable and nonfading colors, and in a wide range of translucencies.

The material is substantially stable in the temperature range of −70 to +210F, and its mechanical properties remain without appreciable change. It has a low dielectric power factor, high dielectric strength and arc resistance, and good dimensional stability.

Its specific gravity is 1.47 to 1.52, and its tensile strength varies from 8,000 to 13,000 psi.

It is compression molded at temperatures ranging from 280 to 340F with pressures from 1,500 to 6,000 psi.

14–19. Melamine. These resins are also widely used as adhesives for plywoods, frames, veneers, bonded woods, and laminated papers.

Molded resins are used for packaging, closures, buttons, terminal boxes, distributor heads, and magnetos.

14–20. Polyvinyls. A useful group of resinous compounds of considerable commercial importance are obtained as the derivatives of acetylene and acetic acid, which produce vinyl acetate, while acetylene and hydrochloric acid yield vinyl chloride. These two products are further polymerized to yield copolymer vinyl, which is suitable for extrusion and injection molding.

These resins may be compounded according to various formulas to produce materials which are either hard, and of the thermosetting group, or elastomeric. The latter are plastic, flexible, and rubberlike at ordinary temperatures.

The acetates are thermoplastic materials and are tasteless, odorless, nontoxic, light in weight, and slow burning. When filled, they may be used as plastic woods and moldings. But, because of their solubility in various common solvents, they find their widest application as adhesives and coatings for paper, cloth, metal, leather, and wood.

Polyvinyl chloride plastics are characterized by a high resistance to chemicals, and their moisture absorption is practically nil. The resin finds its widest use in a highly plasticized form, and, because of its rubberlike properties, it is used for gaskets, flexible tubing lining for acid tanks, and wire insulation.

The copolymer resins are thermoplastic and are inert to most organic acids, alkalies, water, alcohols, grease, and fats; but they are soluble in chlorinated hydrocarbons, ketones, and certain organic acids. They are free from toxicity, odor, and taste and are slow burning. These resins combine the best properties of the acetates and chlorides. They are outstanding in their adaptability to injection molding because of their strength, rigidity, and accuracy of molding. They are beautifully colored, tough, nonwarping, and nonshrinking; and they have water and chemical resistance and high dielectric strength. The resin may be milled, calendered, extruded, or molded. It may also be dissolved and used for coatings for food containers, for waterproofing raincoats, and for coating paper cups and plates and wood.

14–21. Molding. Useful plastic products are manufactured by casting, or more commonly by molding, natural and synthetic resins furnished as granules, powders, preformed briquettes, or blanks. Certain features of the molding technique are similar to those associated with the production of metallic parts by pressure die-casting, permanent mold- and even sand-casting processes. Fundamentals of die design—such as provision of fillets, symmetry of sections, draft allowance, gating, temperatures and cooling rates, mold materials and mold life, dimensional tolerances, and production capacities—are factors equally applicable to the economical and efficient production of plastics as well as metals. As such, they are the concern of the engineer.

Plastic molding is conducted by means of processes known as compression and injection. Extrusion for the production of rods, bars, tubes, and strip of various shapes is generally considered as injection molding because of basic similarities.

14–22. Mold Materials. All forms of plastics molding are carried out in molds, the component parts of which are made of steel selected for specific properties such as machinability, hardness, dimensional stability, and corrosion resistance.

The steels most commonly used are the case-carburizing type SAE 1025, 3110, 3115, and 3310. Also used are the oil-hardening nondeforming tool steels. After a suitable heat treatment to develop hardness, the mold is polished to remove all surface irregularities and is then usually plated with chromium which, besides making further repolishing unnecessary, also provides other desirable advantages over the unplated mold.

Stainless steel has also been used for molds because of its hardness, its ability to withstand the effect of some plastics, and its resistance to moisture. Beryllium-copper alloys are also available as mold material and may quite possibly be used.

Mold cavities are machined by the usual method of producing dies and by a specialized process called *hobbing*, which consists of forcing a master punch of hardened steel into the surface of the low-carbon die block under pressures ranging from 50 to 200 tons. Provided the preliminary preparation (such as grinding of the die block) has been done, the hobbed surface will have a fine, polished finish, and only slight scraping or machining will be necessary to remove any irregularity by an unequal metal flow.

14–23. Compression Molding. Compression molding utilizes a granulated or preformed resinous material, which is placed in the required amounts in cavities of a heated mold constituting the lower half of the complete die or mold. The mold, subsequently closed by pressure, is simultaneously heated to plasticize and polymerize or cure the resin. The application of heat and pressure converts the resin to a semiliquid and increases its flowability to fill all cavities of the mold. Material in excess of that required to fill the mold impressions completely is forced out and is contained between the mold faces. This flash or fin must be removed when the part is finished. After a brief and specific lapse of time—usually from 1 to 5 min, depending on the character, thickness, pressure, temperature, and size of the molding—the mold is opened and the still warm parts are ejected.

Compression molds are most frequently heated by circulating steam or hot water through passages provided in the metal dies. In continuous operating automatic installations, the dies may be heated by electrical resistance.

The molds may consist of a single cavity, as when a large part is molded, or may contain multiple cavities for the production of small parts.

Compression molds are usually attached to the stationary and movable platens of a hydraulic press capable of exerting required pressures in the amounts listed in Table 14–6.

TABLE 14–6

COMPRESSION MOLDING PRESSURES AND TEMPERATURES

Type of Resin	Pressure (Psi)	Temperature (F)
Phenolics	2,000–8,000	270–360
Ureas	1,500–6,000	290–325
Melamine	1,000–7,000	280–340

Surface finishes, distortion, shrinkage, and cracking of the parts during molding are controlled by the correlation of three factors—time, pressure, and temperature.

The advantages of compression molding include its adaptation for molding parts too large for the injection method and its economy. It is the least expensive of the molding processes.

Thermosetting resins are almost always molded by compression, while the thermoplastic materials are molded by either compression or injection. A cross-section of a common type of compression mold is shown in Fig. 14–4.

Compression molding of the phenolics and ureas and melamine is accomplished by three methods: (1) *manually* in "hand molds," where the molds are placed and removed by the operator; (2) *semiautomatically*, where the molds are fastened to the platens of the press and the parts are forced free as the press opens the molds; (3) *automatically*, where the operation of weighing or measuring, charging and closing and opening the mold, and ejecting and removing the pieces from the mold are carried out by suitable mechanical and electrical means. As in other operations involving quantity production, the selection of the equipment and methods will be dictated largely by the number of similar parts required.

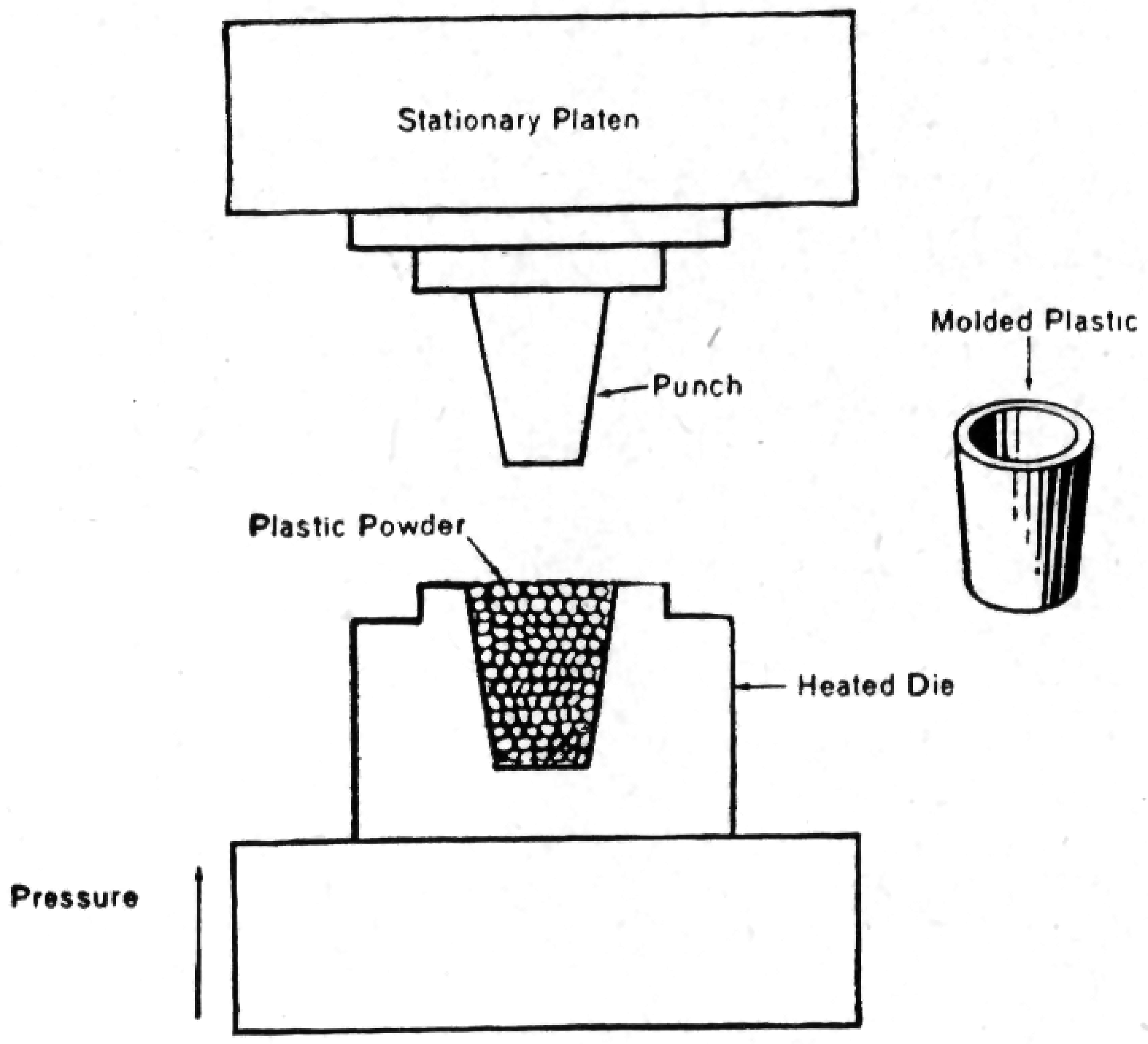
Stationary Platen
Punch
Molded Plastic
Plastic Powder
Heated Die
Pressure

Fig. 14–4. Sectional view of a compression mold.

14–24. Injection Molding. This method of molding is primarily applicable to the production of thermoplastic parts. (In this process, in contrast to compression molding, in which cold material is placed in heated molds), the resin is first heated to attain a soft or semiliquid state. It is then injected into a cold mold from a preheating cylinder through a sprue, runner, and gate by a piston which may be mechanically, hydraulically, or pneumatically operated. After passing through the orifice, the plastic substance fills the mold cavities in a manner similar to pressure die-casting. Usually the dies are maintained at a constant, cool temperature by the circulation of water, to permit the plastic to become rigid and maintain its shape when ejected from the mold.

A sectional view of an injection mold is shown in Fig. 14–5.

In general, injection molding is adaptable to the production of more intricate shapes than compression molding, and is more simple in its basic principle. Its other advantages are: (1) there are higher production rates because of much more rapid press operation; (2) the dies are not alternately heated and cooled; (3) the dies may contain a large number of impressions, thus producing many parts in one molding cycle; (4) there are smaller material losses and lower finishing costs. With proper die design, production is conditioned by the time required to chill and harden the material in the mold. This is largely a function of the type of compound and the thickness of the part.

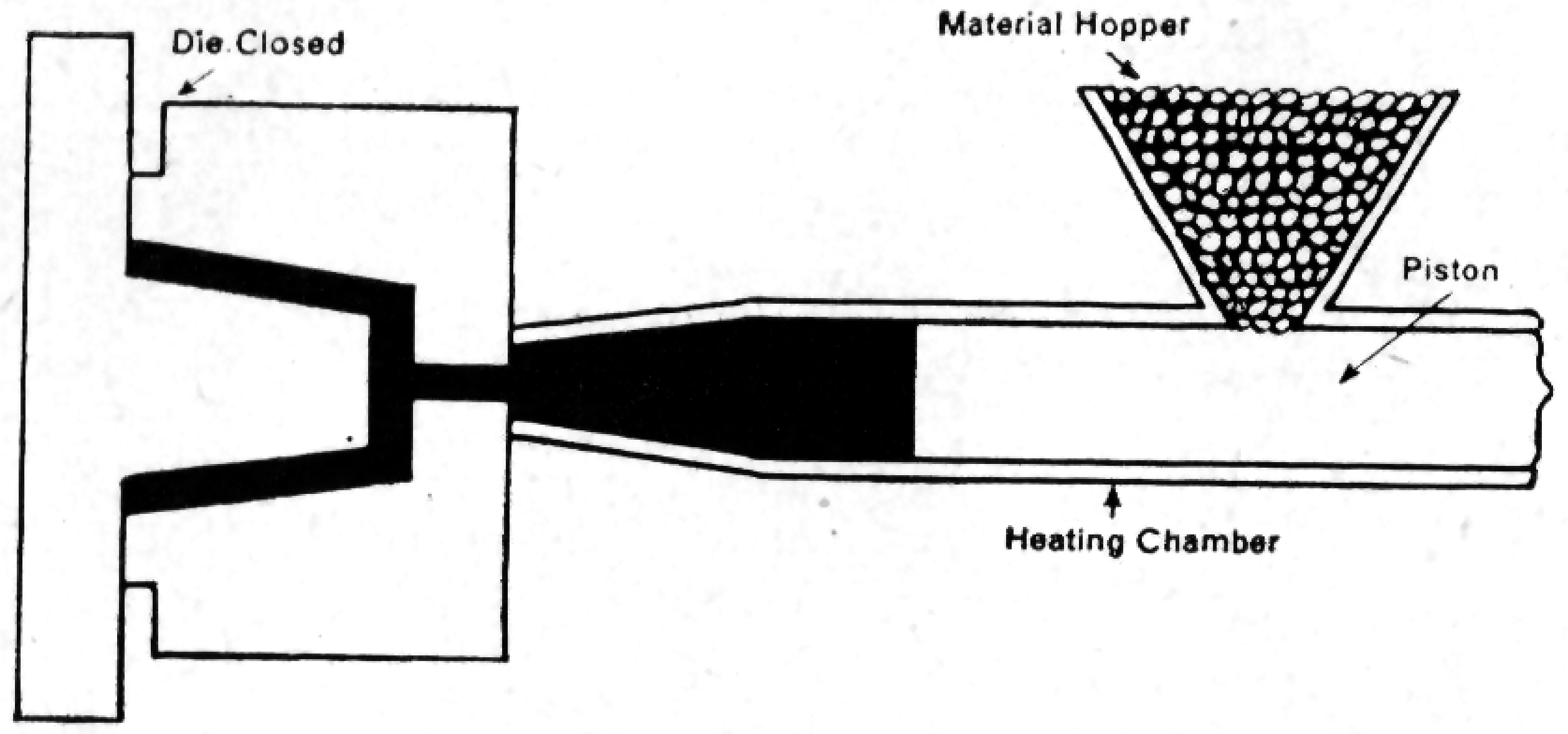
Die Closed
Material Hopper
Piston
Heating Chamber

Fig. 14–5. Sectional view of an injection mold.

In order to maintain fluidity, injection molded materials must attain a high initial temperature to avoid premature hardening from contact with the cool mold. For this reason, resins sensitive to high temperatures, such as cellulose nitrates, are not suitable for molding by this method.

As in compression molding, sufficient pressure in conjunction with other proper conditions is necessary for the production of a smooth, lustrous finish on the plastics. Generally, the pressures vary between 15,000 and 20,000 psi of surface area, although, in some instances, pressure of 30,000 psi have been used. The temperature of the resins is limited to about 385F.

A sectional view of the operating parts of an injection molding machine is shown in Fig. 14–6. A large injection molding machine is shown in Fig. 14–7.

14–25. Transfer Molding. This form of molding embodies some of the features of both compression and injection processes. It is commonly

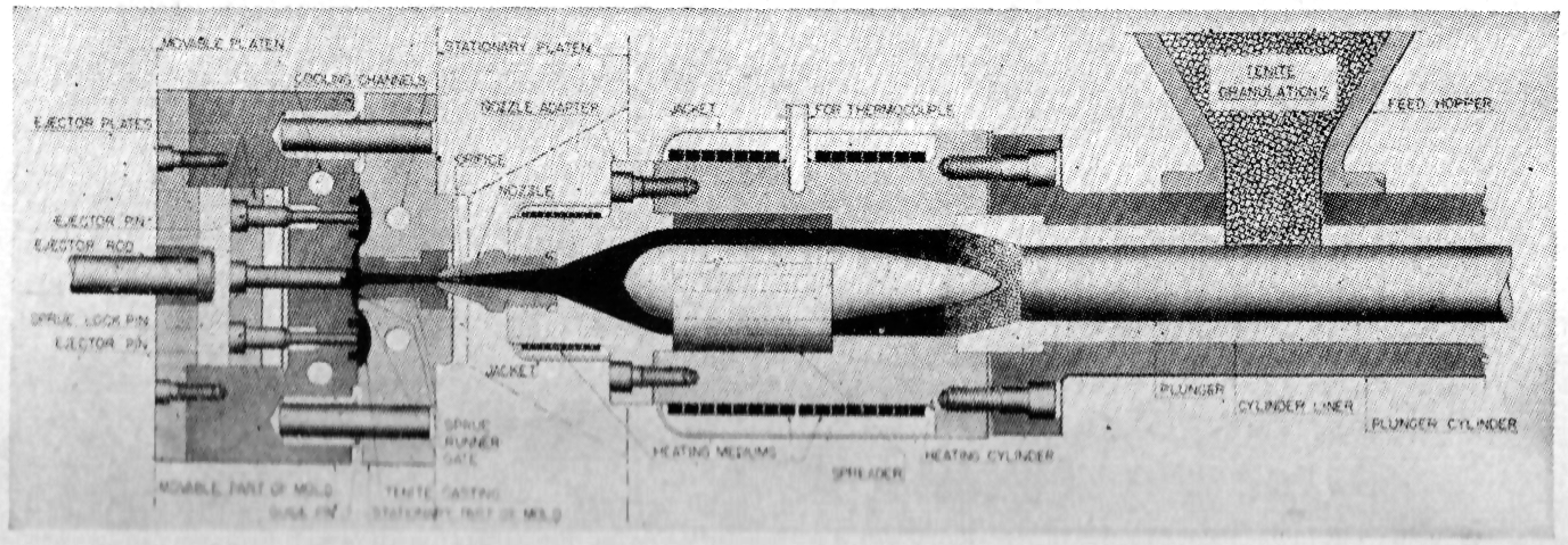
MOVABLE PLATEN
STATIONARY PLATEN
COOLING CHANNELS
EJECTOR PLATES
NOZZLE ADAPTER
JACKET
FOR THERMOCOUPLE
TENITE GRANULATIONS
FEED HOPPER
ORIFICE
NOZZLE
EJECTOR PIN
EJECTOR ROD
SPRUE LOCK PIN
EJECTOR PIN
JACKET
SPRUE
RUNNER
GATE
PLUNGER
CYLINDER LINER
PLUNGER CYLINDER
HEATING MEDIUMS
SPREADER
HEATING CYLINDER
MOVABLE PART OF MOLD
TENITE CASTING
STATIONARY PART OF MOLD

Fig. 14–6. Sectional view illustrating general methods of injection molding.

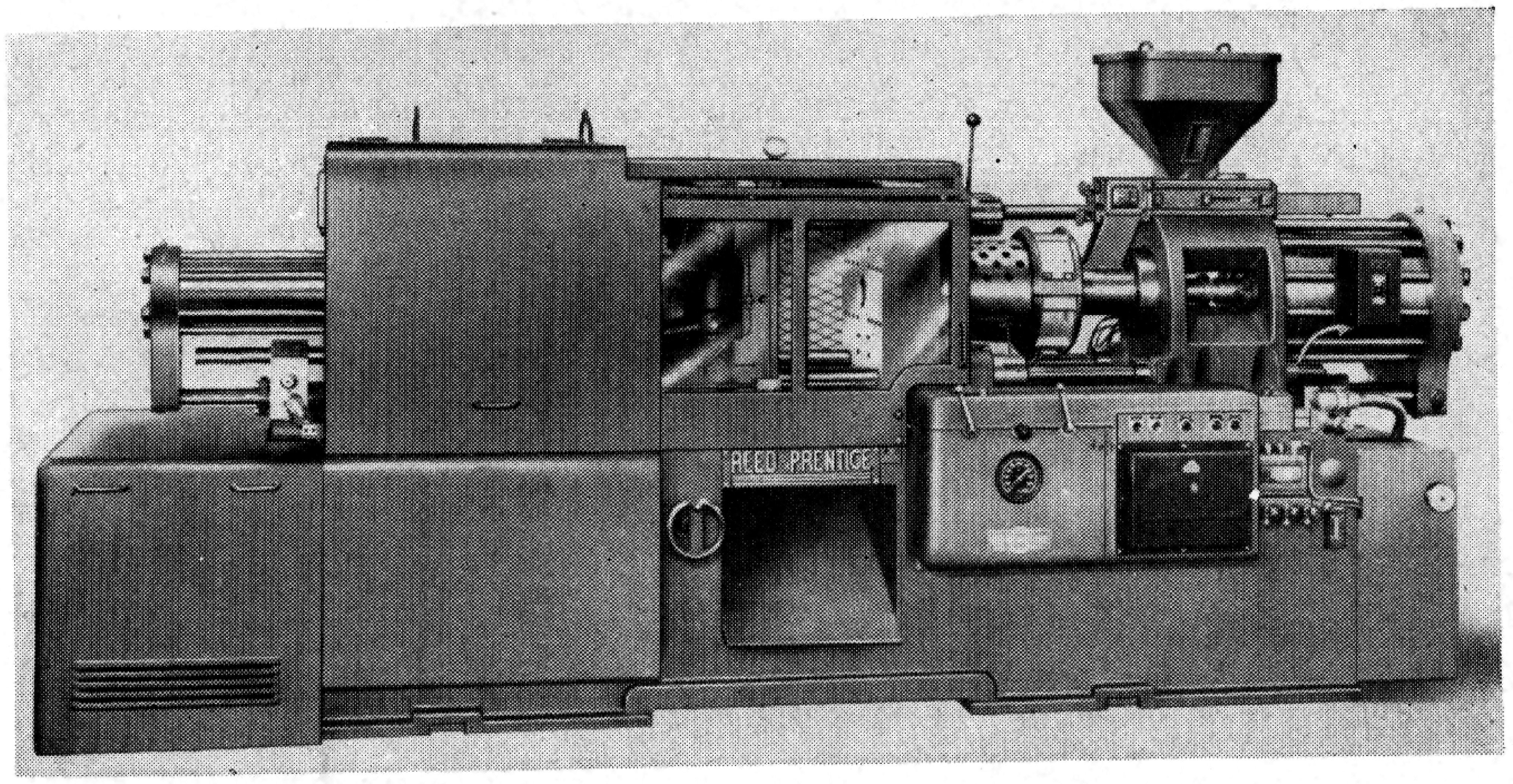

FIG. 14–7. Large injection machine for molding plastic parts. (Courtesy of Reed-Prentice Corp., Worcester, Mass.)

used in the production of intricate thermosetting plastics involving the use of glass or metallic inserts whose production would be difficult or impossible by compression or the conventional injection methods. The molding material, contained in a well in which it is brought to a semiliquid state, is forced by a piston or plunger through an orifice into a closed mold where it remains until cured. A transfer mold is shown in Fig. 14–8.

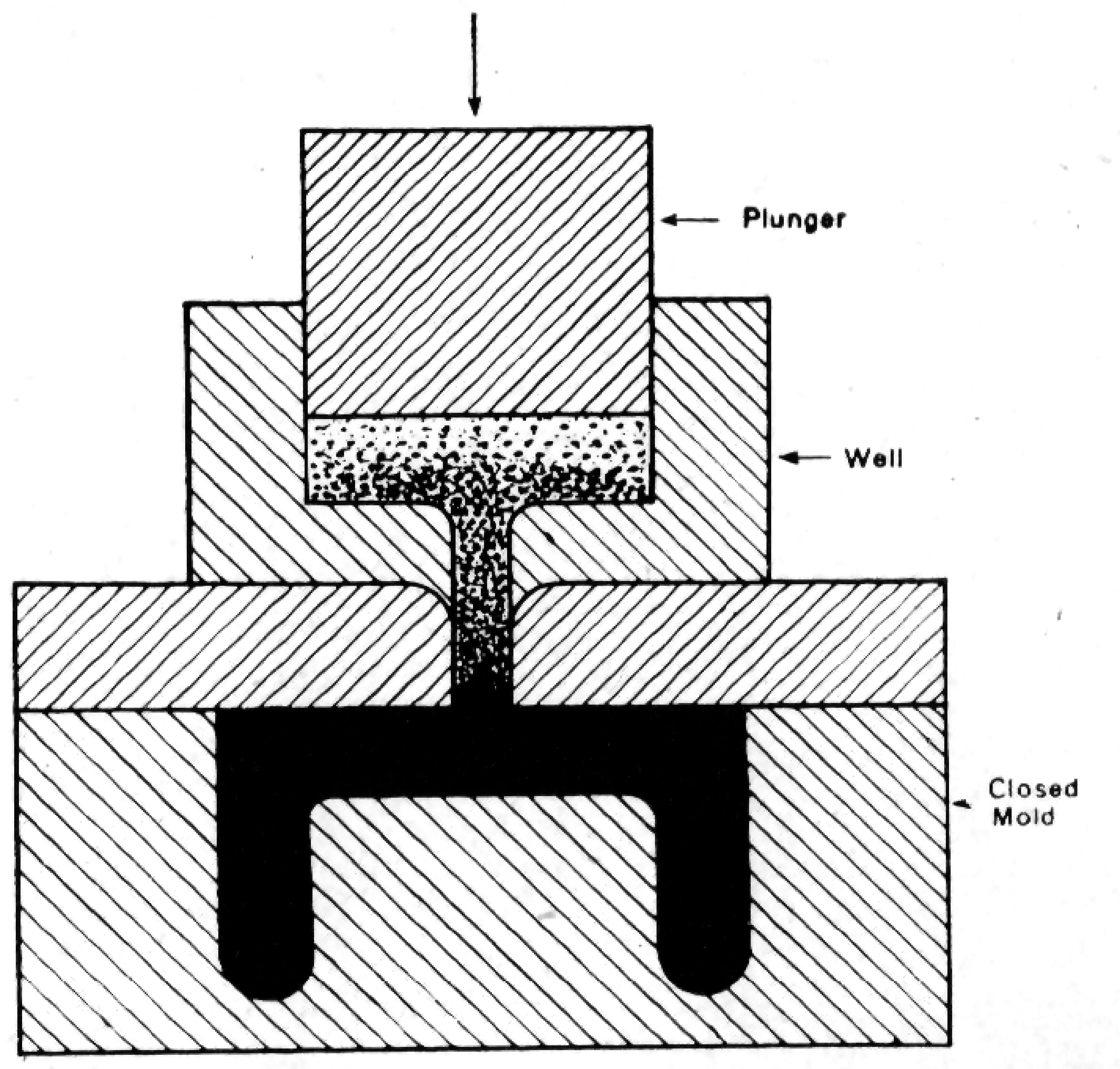

FIG. 14–8. Sectional view of transfer mold.

Some of the advantages of transfer molding are: (1) high production rates are possible because of a short molding cycle; (2) close dimensional accuracy is obtainable because the mold is closed when the resin enters; (3) finishing costs are less because no fins or flash need be removed; (4) rejections because of flow marks, gas pockets, and blisters are reduced, since occluded gases are dispelled before the material enters the mold; and (5) inserts may be placed and accurately held in the finished part.

14–26. Extrusion. Extrusion is a process whereby thermoplastic resinous substances, after being heated to a highly plasticized state, are forced out of a cylinder (usually by a screw feed device) through an orifice, provided in a die, which conforms to the shape of the desired part. Essentially the process is similar to the extrusion of aluminum or magnesium alloys in a large variety of shapes for a wide diversity of uses.

It is an economical and productive method of producing strips, tubes, rods, and irregular shapes in considerable lengths as required for moldings and decorative profiles.

As the hot plastic strip or tube emerges from the die it is cooled by air and is supported by a continuously moving conveyor canvas belt whose speed of travel is synchronized with the rate of extrusion.

Extruded materials include cellulose acetate, cellulose acetate butyrate, ethyl cellulose, vinyl chloride, polystyrene, and methyl methacrylate.

14–27. Cold-Molding. Certain plastics compounded of synthetic and natural binders and organic or inorganic fillers are cold-formed and later baked to effect their final strength and hardness. By this method, materials may be produced with considerably higher asbestos content for heat resistance and retention of strength at elevated temperatures than is possible by hot-molding of similarly filled phenolics.

The binders consist of asphalt, cement, and phenolic resin. After being compressed in the mold until it has fully assumed the required form, the part is removed and baked in ovens for a period of time, varying with the temperature and the size of the piece. Normally from one to three days suffices. Cold-molded plastics do not have the smooth, lustrous surface finish of the hot-molded materials, because they are not cured under heat and pressure.

Typical applications of cold-molded parts are battery boxes, rheostat and switch bases, electric light plugs, connector plugs for flat irons, and handles and knobs for cooking utensils.

14–28. Laminated Materials. Laminated sheets are made by surface-coating such materials as paper or cloth with liquid resin. After drying, the sheets are piled one upon the other to the desired thickness, and are cured at a temperature between 300 and 350F and under pressure up to 2,500 lb, applied through heated steel rolls or polished plates. After curing, the sheets are removed and fabricated to the required shape.

Laminated tubing is most commonly made by wrapping the material around a mandrel between three heated rolls. The interlayer of resin is softened and is bonded with the material. After the proper wall thickness is attained, the tube is placed in a heated oven before the mandrel is removed.

Laminated material is an extremely useful plastic. Many applications are found in electrical products because of its strength and excellent dielectric properties. Its high strength is also an advantage when it is used in timing gears, although in this application its resilience and sound-deadening qualities are of major interest.

Plywood in sheet form falls into the category of laminated material. The manufacture of this product is, however, an industry in itself and is generally not considered a part of the plastics industry.

QUESTIONS AND PROBLEMS

1. Make a comparative list of the advantages of plastics and metals.
2. Define "plastics."
3. Compare thermoplastics and thermosetting materials as to materials, molding, stability of dimensions, appearance, costs, and applications.
4. Describe compression, transfer, and injection type molding.
5. List types of fillers used in plastics and how each affects the final properties.
6. Give the names of five thermoplastic resins.
7. Give the names of five thermosetting resins.
8. What characterizes plastics made from urea and formaldehyde?
9. Compare the properties of cellulose nitrate and cellulose acetate plastics.
10. What types of steels may be used for dies for molding various plastics?
11. Define "hobbing."
12. What materials are extruded?
13. What types of materials are "cold-molded?"

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CHAPTER 15

CLASSIFICATIONS OF STEELS

The possible bases for classifying steels are many and varied. For example, their classification may be based on the process by which they are produced such as Bessemer, basic or acid open-hearth, or the electric furnace. On the basis of the degree to which they have been deoxidized they may be classified as fully deoxidized, semideoxidized, or rimming. The basis may be: the amount of carbon they contain, such as mild, medium, or high carbon; the amount of the predominating alloying element, such as nickel, manganese, etc.; or the use for which they are principally intended, as free machining, forging, or tool steels. As discussed previously steels are also classified on the basis of the size of the crystalline grains as fine- or coarse-grained.

A reasonable familiarity with the various steels and their latent properties is very desirable for all engineers, as it will enable them to make a proper selection to meet required physical specifications.

None of these bases of classification, however, is sufficiently inclusive and exclusive to adequately describe the steels, since several of the factors overlap. For example, a mild steel may be the product of either the Bessemer or the open-hearth processes.

It was with a view to simplification and to the establishment of a standard method of identification that the Society of Automotive Engineers established the first Iron and Steel Specifications in 1911. The numerical system which developed from this beginning makes it possible to use on drawings numerals that partially describe the composition of the steel covered by such numbers. In the SAE system, each type of steel is designated by a number, the first digit of which indicates the type of steel. The second digit generally indicates the approximate amount of the predominating alloy element in low-alloy steels, while the last two or three digits express the average amount of carbon in "points" or one-hundredths of 1 per cent.

Nickel steels are designated by the numeral 2. Thus, the number 2330 designates a nickel steel containing approximately 3 per cent (3.25 to 3.75) nickel and an average of 0.3 per cent (0.28 to 0.33) carbon. The Mn, P, S, and Si are within specified limits.

The basic numerals for the various types of SAE steels are as follows:

Type of Steel	*Numerals (and Digits)*
Carbon Steels	1xxx
Plain carbon	10xx
Free cutting (screw stock)	11xx

Type of Steel	*Numerals (and Digits)*
Manganese Steels	13xx
Nickel Steels	2xxx
3.50 per cent nickel	23xx
5.00 per cent nickel	25xx
Nickel-Chromium Steels	3xxx
1.25 per cent nickel, 0.60 per cent chromium	31xx
1.75 per cent nickel, 1.00 per cent chromium	32xx
3.50 per cent nickel, 1.50 per cent chromium	33xx
Corrosion and heat-resisting steels	30xxx
Molybdenum Steels	4xxx
Carbon-molybdenum	40xx
Chromium-molybdenum	41xx
Chromium-nickel-molybdenum	43xx
Nickel-molybdenum; 1.75 per cent nickel	46xx
Nickel-molybdenum; 3.50 per cent nickel	48xx
Chromium Steels	5xxx
Low-chromium	51xx
Medium-chromium	52xxx
Corrosion and heat resisting	51xxx
Chromium-Vanadium Steels	6xxx
1 per cent chromium	61xx
Silicon-Manganese Steels	9xxx
2 per cent silicon	92xx

Formerly, the prefix "X" was used in numerous instances to denote variations in the range of some elements, and the prefix "T" was used with the Manganese Steels (1300 series) to indicate variation in the alloy range; see Table 15–1. This practice has been discontinued and variations in the chromium, manganese, and sulphur are now indicated by changing the final digit of the numerical designation.

It has also been found necessary to depart from the basic system in some instances, such as with the numbers selected for various heat and corrosion resistant alloys.

The American Iron and Steel Institute has issued standard steel compositions using a numerical system similar to that of the Society of Automotive Engineers, except that letter prefixes are added to indicate the method used in manufacturing the steel. The code for these prefix letters is as follows:

A is basic open-hearth alloy steel.
B is acid Bessemer carbon steel.
C is basic open-hearth carbon steel.
D is acid open-hearth carbon steel.
E is electric furnace steel.
CB is basic open-hearth or acid Bessemer carbon steel.

Thus, A2340 denotes a basic open-hearth alloy steel, conforming to the 2340 specification, while E4342 denotes an electric furnace steel of the chromium-nickel-molybdenum type. Through the cooperative efforts of the Technical Committee on Alloy Steel of American Iron and Steel Institute and the Iron and Steel Division of the Society of Automotive

TABLE 15–1

SAE Official Steel Specifications

CARBON STEELS

S.A.E. No.	Carbon Range	Mang. Range	Phos. Max.	Sulfur Max.
1010	.05-.15	.30- .60	.045	.055
1015	.10-.20	.30- .60	.045	.055
X1015	.10-.20	.70-1.00	.045	.055
1020	.15-.25	.30- .60	.045	.055
X1020	.15-.25	.70-1.00	.045	.055
1025	.20-.30	.30- .60	.045	.055
X1025	.20-.30	.70-1.00	.045	.055
1030	.25-.35	.60- .90	.045	.055
1035	.30-.40	.60- .90	.045	.055
1040	.35-.45	.60- .90	.045	.055
X1040	.35-.45	.40- .70	.045	.055
1045	.40-.50	.60- .90	.045	.055
X1045	.40-.50	.40- .70	.045	.055
1050	.45-.55	.60- .90	.045	.055
X1050	.45-.55	.40- .70	.045	.055
1055	.50-.60	.60- .90	.040	.055
X1055	.50-.60	.90-1.20	.040	.055
1060	.55-.70	.60- .90	.040	.055
1065	.60-.75	.60- .90	.040	.055
X1065	.60-.75	.90-1.20	.040	.055
1070	.65-.80	.60- .90	.040	.055
1075	.70-.85	.60- .90	.040	.055
1080	.75-.90	.60- .90	.040	.055
1085	.80-.95	.60- .90	.040	.055
1090	.85-1.00	.60- .90	.040	.055
1095	.90-1.05	.25- .50	.040	.055

FREE CUTTING STEELS

S.A.E. No.	Carbon Range	Mang. Range	Phos. Range	Sulfur Range
1112	.08-.16	.60- .90	.09-.13	.10 -.20
X1112	.08-.16	.60- .90	.09-.13	.20- .30
1115	.10-.20	.70-1.00	.045 max.	.075-.15
1120	.15-.25	.60- .90	.045 max.	.075-.15
X1314	.10-.20	1.00-1.30	.045 max.	.075-.15
X1315	.10-.20	1.30-1.60	.045 max.	.075-.15
X1330	.25-.35	1.35-1.65	.045 max.	.075-.15
X1335	.30-.40	1.35-1.65	.045 max.	.075-.15
X1340	.35-.45	1.35-1.65	.045 max.	.075-.15

TABLE 15–1 (Continued)

MANGANESE STEELS

S.A.E. No.	Carbon Range	Mang. Range	Phos. Max.	Sulfur Max.
T1330	.25-.35	1.60-1.90	.040	.050
T1335	.30-.40	1.60-1.90	.040	.050
T1340	.35-.45	1.60-1.90	.040	.050
T1345	.40-.50	1.60-1.90	.040	.050
T1350	.45-.55	1.60-1.90	.040	.050

NICKEL STEELS

S.A.E. No.	Carbon Range	Mang. Range	Phos. Max.	Sulfur Max.	Nickel Range
2015	.10-.20	.30-.60	.040	.050	.40- .60
2115	.10-.20	.30-.60	.040	.050	1.25-1.75
2315	.10-.20	.30-.60	.040	.050	3.25-3.75
2320	.15-.25	.30-.60	.040	.050	3.25-3.75
2330	.25-.35	.50-.80	.040	.050	3.25-3.75
2335	.30-.40	.50-.80	.040	.050	3.25-3.75
2340	.35-.45	.60-.90	.040	.050	3.25-3.75
2345	.40-.50	.60-.90	.040	.050	3.25-3.75
2350	.45-.55	.60-.90	.040	.050	3.25-3.75
2515	.10-.20	.30-.60	.040	.050	4.75-5.25

NICKEL-CHROMIUM STEELS

S.A.E. No.	Carbon Range	Mang. Range	Phos. Max.	Sulfur Max.	Nickel Range	Chromium Range
3115	.10-.20	.30-.60	.040	.050	1.00-1.50	.45- .75
3120	.15-.25	.30-.60	.040	.050	1.00-1.50	.45- .75
3125	.20-.30	.50-.80	.040	.050	1.00-1.50	.45- .75
3130	.25-.35	.50-.80	.040	.050	1.00-1.50	.45- .75
3135	.30-.40	.50-.80	.040	.050	1.00-1.50	.45- .75
3140	.35-.45	.60-.90	.040	.050	1.00-1.50	.45- .75
X3140	.35-.45	.60-.90	.040	.050	1.00-1.50	.60- .90
3145	.40-.50	.60-.90	.040	.050	1.00-1.50	.45- .75
3150	.45-.55	.60-.90	.040	.050	1.00-1.50	.45- .75
3215	.10-.20	.30-.60	.040	.050	1.50-2.00	.90-1.25
3220	.15-.25	.30-.60	.040	.050	1.50-2.00	.90-1.25
3230	.25-.35	.30-.60	.040	.050	1.50-2.00	.90-1.25
3240	.35-.45	.30-.60	.040	.050	1.50-2.00	.90-1.25
3245	.40-.50	.30-.60	.040	.050	1.50-2.00	.90-1.25
3250	.45-.55	.30-.60	.040	.050	1.50-2.00	.90-1.25
3312	max. 0.17	.30-.60	.040	.050	3.25-3.75	1.25-1.75
3325	.20-.30	.30-.60	.040	.050	3.25-3.75	1.25-1.75
3335	.30-.40	.30-.60	.040	.050	3.25-3.75	1.25-1.75
3340	.35-.45	.30-.60	.040	.050	3.25-3.75	1.25-1.75

TABLE 15–1 (Continued)

NICKEL-CHROMIUM STEELS (Continued)

S. A. E. No.	Carbon Range	Mang. Range	Phos. Max.	Sulfur Max.	Nickel Range	Chrom. Range
3415	.10-.20	.30-.60	.040	.050	2.75-3.25	.60- .95
3435	.30-.40	.30-.60	.040	.050	2.75-3.25	.60- .95
3450	.45-.55	.30-.60	.040	.050	2.75-3.25	.60- .95

MOLYBDENUM STEELS

S. A. E. No.	Carbon Range	Mang. Range	Phos. Max.	Sulfur Max.	Chrom. Range	Nickel Range	Moly. Range
4130	.25-.35	.50-.80	.040	.050	.50- .80	....	.15-.25
X4130	.25-.35	.40-.60	.040	.050	.80-1.10	....	.15-.25
4135	.30-.40	.60-.90	.040	.050	.80-1.10	....	.15-.25
4140	.35-.45	.60-.90	.040	.050	.80-1.10	....	.15-.25
4150	.45-.55	.60-.90	.040	.050	.80-1.10	....	.15-.25
4320	.15-.25	.40-.70	.040	.050	.30- .60	1.65-2.00	.20-.30
4340	.35-.45	.50-.80	.040	.050	.50-. 80	1.50-2.00	.30-.40
X4340	.35-.45	.50-.80	.040	.050	.60- .90	1.50-2.00	.20-.30
4345	.40-.50	.50-.80	.040	.050	.60- .90	1.50-2.00	.15-.25
4615	.10-.20	.40-.70	.040	.050	....	1.65-2.00	.20-.30
4620	.15-.25	.40-.70	.040	.050	....	1.65-2.00	.20-.30
4640	.35-.45	.50-.80	.040	.050	....	1.65-2.00	.20-.30
4815	.10-.20	.40-.60	.040	.050	....	3.25-3.75	.20-.30
4820	.15-.25	.40-.60	.040	.050	....	3.25-3.75	.20-.30

CHROMIUM STEELS

S. A. E. No.	Carbon Range	Mang. Range	Phos. Max.	Sulfur Max.	Chromium Range
5120	.15- .25	.30-.60	.040	.050	.60- .90
5140	.35- .45	.60-.90	.040	.050	.80-1.10
5150	.45- .55	.60-.90	.040	.050	.80-1.10
52100	.95-1.10	.20-.50	.030	.035	1.20-1.50

CHROMIUM-VANADIUM STEELS

S. A. E. No.	Carbon Range	Mang. Range	Phos. Max.	Sulfur Max.	Chrom. Range	Vanadium	
						Min.	Desired
6115	.10- .20	.30-.60	.040	.050	.80-1.10	.15	.18
6120	.15- .25	.30-.60	.040	.050	.80-1.10	.15	.18
6125	.20- .30	.60-.90	.040	.050	.80-1.10	.15	.18
6130	.25- .35	.60-.90	.040	.050	.80-1.10	.15	.18
6135	.30- .40	.60-.90	.040	.050	.80-1.10	.15	.18

TABLE 15–1 (Continued)

CHROMIUM-VANADIUM STEELS (Continued)

S.A.E. No.	Carbon Range	Mang. Range	Phos. Max.	Sulfur Max.	Chrom. Range	Vanadium	
						Min.	Desired
6140	.35- .45	.60-.90	.040	.050	.80-1.10	.15	.18
6145	.40- .50	.60-.90	.040	.050	.80-1.10	.15	.18
6150	.45- .55	.60-.90	.040	.050	.80-1.10	.15	.18
6195	.90-1.05	.20-.45	.030	.035	.80-1.10	.15	.18

TUNGSTEN STEELS

S. A. E. No.	Carbon Range	Mang. Max.	Phos. Max.	Sulfur Max.	Chromium Range	Tungsten Range
71360	.50-.70	.30	.035	.040	3.00-4.00	12.00-15.00
71660	.50-.70	.30	.035	.040	3.00-4.00	15.00-18.00
7260	.50-.70	.30	.035	.040	.50-1.00	1.50- 2.00

SILICON-MANGANESE STEELS

S. A. E. No.	Carbon Range	Mang. Range	Phos. Max.	Sulfur Max.	Silicon Range
9255	.50-.60	.60-.90	.040	.050	1.80-2.20
9260	.55-.65	.60-.90	.040	.050	1.80-2.20

CORROSION- AND HEAT-RESISTING ALLOYS

S. A. E. No.	Carbon Max.	Mang. Max.	Phos. Max.	Sulfur Max.	Silicon Max.	Chromium Range	Nickel Range
30905	.08	.20-.70	.030	.030	.75	17.00-20.00	8.00-10.00
30915	.09-.20	.20-.70	.030	.030	.75	17.00-20.00	8.00-10.00
51210	.12	.60	.030	.030	.50	11.50-13.00	....
X51410	.12	.60	.030	.15-.50	.50	13.00-15.00	....
51335	.25-.40	.60	.030	.030	.50	12.00-14.00	....
51510	.12	.60	.030	.030	.50	14.00-16.00	....
51710	.12	.60	.030	.030	.50	16.00-18.00	....

Engineers Standards Committee, the AISI and SAE systems now correspond closely. Tables 15–2A and B* give the standard carbon and free cutting steels. Tables 15–3A and B* give the revised AISI standard alloy steel compositions.

**Metal Progress Data Sheet* (November, 1946).

TABLE 15–2A

Standard Carbon Steels, as Revised July 1, 1946

Basic Openhearth and Acid Bessemer Carbon Steels

A.I.S.I. Number	Semi-finish	Hot Rolled Bars	Cold Finished Bars	Rods	Wire	C	Mn	P (c)	S (c)	1946 S.A.E. Number
C 1006	—	—	—	√	√	0.08 max.	0.25-0.40	0.040	0.050	1006
C 1008	√	√	√	√	√	0.10 max.	0.30-0.50	0.040	0.050	1008
C 1010	√	√	√	√	√	0.08-0.13	0.30-0.60	0.040	0.050	1010
C 1012	√	√	—	√	√	0.10-0.15	0.30-0.60	0.040	0.050	....
C 1013	—	—	—	√	√	0.11-0.16	0.60-0.90	0.040	0.050	....
C 1015	√	√	√	√	√	0.13-0.18	0.30-0.60	0.040	0.050	1015
C 1016	√	√	√	√	√	0.13-0.18	0.60-0.90	0.040	0.050	{X1015 1016
C 1017	√	√	—	√	√	0.15-0.20	0.30-0.60	0.040	0.050	1017
(e)	√	√	√	√	—	0.15-0.20	0.60-0.90	0.040	0.050	1018
C 1019	√	√	√	√	√	0.15-0.20	0.70-1.00	0.040	0.050	1019
C 1020	√	√	√	√	√	0.18-0.23	0.30-0.60	0.040	0.050	1020
C 1022	√	√	√	√	√	0.18-0.23	0.70-1.00	0.040	0.050	{X1020 1022
C 1023	√	√	—	—	—	0.20-0.25	0.30-0.60	0.040	0.050	....
C 1025	√	√	√	√	√	0.22-0.28	0.30-0.60	0.040	0.050	1025
(e)	√	√	√	√	—	0.22-0.28	0.40-0.60	0.040	0.050	1026
C 1030	√	√	√	√	√	0.28-0.34	0.60-0.90	0.040	0.050	1030
(e)	√	√	√	√	—	0.30-0.36	0.60-0.90	0.040	0.050	1033
C 1034	—	—	—	√	√	0.32-0.38	0.50-0.80	0.040	0.050	....
C 1035	√	√	√	—	—	0.32-0.38	0.60-0.90	0.040	0.050	1035
C 1038	—	—	—	√	√	0.35-0.42	0.60-0.90	0.040	0.050	....
C 1040	√	√	√	√	√	0.37-0.44	0.60-0.90	0.040	0.050	1040
C 1041	—	—	—	√	√	0.36-0.44	1.35-1.65	0.040	0.050	....
C 1043	√	√	—	—	—	0.40-0.47	0.70-1.00	0.040	0.050	....
C 1045	√	√	√	—	—	0.43-0.50	0.60-0.90	0.040	0.050	1045
D 1049	—	—	—	√	√	0.43-0.50	0.50-0.80	0.050	0.050	....
C 1050	√	√	√	—	—	0.48-0.55	0.60-0.90	0.040	0.050	1050
C 1051	—	—	—	√	—	0.45-0.56	0.85-1.15	0.040	0.050	....
(e)	√	√	√	√	—	0.47-0.55	1.20-1.50	0.040	0.050	1052
C 1054	—	—	—	√	—	0.50-0.60	0.50-0.80	0.040	0.050	....
D 1054	—	—	—	√	√	0.50-0.60	0.50-0.80	0.050	0.050	....
C 1055	√	√	—	—	—	0.50-0.60	0.60-0.90	0.040	0.050	1055
C 1057	—	—	—	√	—	0.50-0.61	0.85-1.15	0.040	0.050	....
C 1059	—	—	—	√	—	0.55-0.65	0.50-0.80	0.040	0.050	....
D 1059	—	—	—	√	√	0.55-0.65	0.50-0.80	0.050	0.050	....
C 1060	—	√	—	√	—	0.55-0.65	0.60-0.90	0.040	0.050	1060
C 1062	—	—	—	√	—	0.54-0.65	0.85-1.15	0.040	0.050	1062
C 1064	—	—	—	√	—	0.60-0.70	0.50-0.80	0.040	0.050	....
D 1064	—	—	—	√	√	0.60-0.70	0.50-0.80	0.050	0.050	1064
C 1065	—	√	—	—	—	0.60-0.70	0.60-0.90	0.040	0.050	....
C 1066	—	—	—	√	—	0.60-0.71	0.85-1.15	0.040	0.050	{X1065 1066
C 1069	—	—	—	√	—	0.65-0.75	0.40-0.70	0.040	0.050	....
D 1069	—	—	—	√	√	0.65-0.75	0.40-0.70	0.050	0.050	....
C 1070	—	√	—	—	—	0.65-0.75	0.60-0.90	0.040	0.050	1070
(e)	√	√	√	√	—	0.70-0.80	0.50-0.70	0.040	0.050	1074
D 1075	—	—	—	√	√	0.70-0.80	0.40-0.70	0.050	0.050	....
C 1075	—	—	—	√	—	0.70-0.80	0.40-0.70	0.040	0.050	....
C 1078	—	√	—	√	—	0.72-0.85	0.30-0.60	0.040	0.050	1078
C 1080	—	√	—	—	—	0.75-0.88	0.60-0.90	0.040	0.050	1080
C 1085	√	√	—	—	—	0.80-0.93	0.70-1.00	0.040	0.050	1085
(e)	√	√	√	√	—	0.82-0.95	0.30-0.50	0.040	0.050	1086
(e)	√	√	√	√	—	0.85-1.00	0.60-0.90	0.040	0.050	1090
C 1095	—	√	√	√	—	0.90-1.05	0.30-0.50	0.040	0.050	1095

TABLE 15–2B

FREE CUTTING STEELS, AS REVISED JULY 1, 1946

Free Cutting Steels

A.I.S.I. Number (a)	Semi-finished Products	Bars (b)	Rods	C	Mn	P (c)	S (c)	1946 S.A.E. Number
B 1006	—	—	(d)	0.08 max.	0.45 max.	0.07-0.12	0.060 max.	....
B 1010	—	√	(d)	0.13 max.	0.30-0.60	0.07-0.12	0.060 max.	....
C 1108	—	—	√	0.08-0.13	0.50-0.80	0.045 max.	0.07-0.12	....
C 1109	√	√	√	0.08-0.13	0.60-0.90	0.045 max.	0.08-0.13	....
B 1111	—	√	√	0.08-0.13	0.70-1.00	0.07-0.12	0.10-0.15	1111
C 1111	—	—	√	0.08-0.13	0.60-0.90	0.045 max.	0.16-0.23	....
B 1112	—	√	√	0.08-0.13	0.70-1.00	0.07-0.12	0.16-0.23	1112
C 1112	—	√	√	0.10-0.16	1.00-1.30	0.045 max.	0.08-0.13	....
B 1113	—	√	√	0.08-0.13	0.70-1.00	0.07-0.12	0.24-0.33	X1112 1113
C 1115	√	√	√	0.13-0.18	0.70-1.00	0.045 max.	0.08-0.13	1115
C 1116	—	√	—	0.14-0.20	1.10-1.40	0.045 max.	0.16-0.23	....
C 1117	—	√	√	0.14-0.20	1.00-1.30	0.045 max.	0.08-0.13	X1314 1117
C 1118	√	√	√	0.14-0.20	1.30-1.60	0.045 max.	0.08-0.13	X1315 1118
C 1120	√	√	√	0.18-0.23	0.70-1.00	0.045 max.	0.08-0.13	....
(e)	√	√	√	0.27-0.34	1.35-1.65	0.045 max.	0.08-0.13	X1330 1132
C 1137	√	√	√	0.32-0.39	1.35-1.65	0.045 max.	0.08-0.13	X1335 1137
C 1141	—	√	√	0.37-0.45	1.35-1.65	0.045 max.	0.08-0.13	X1340 1141
C 1144	—	√	—	0.40-0.48	1.35-1.65	0.045 max.	0.24-0.33	....
C 1145	√	√	—	0.42-0.49	0.70-1.00	0.045 max.	0.04-0.07	1145
C 1151	√	√	—	0.48-0.55	0.70-1.00	0.045 max.	0.08-0.13	1151

During the war, a scarcity of certain alloying elements prevented their use except in such equipment as guns, armor, projectiles, aircraft, and strategic tools, and it became necessary to alter the chemical compositions of many steels in order to release critical elements for emergency use. Since the specific effects of the various elements had been fairly well established, it was found possible to use the available elements and develop alternate compositions which could be substituted satisfactorily for steels of established composition.

These emergency steels were grouped under a new classification, the National Emergency (NE) Standard Steel Compositions, issued jointly by the American Iron and Steel Institute and the Society of Automotive Engineers. At the present time, very few of the original NE compositions remain, the only appreciable group being the nickel-chromium-molybdenum steels, NE94xx, NE97xx, NE98xx, and NE99xx.

Some, such as the 86xx and 87xx, have been standardized by the American Iron and Steel Institute, while others either have been discontinued or the analysis has been adjusted to conform to the older SAE types.

TABLE 15–3A

AISI STANDARD ALLOY STEEL COMPOSITIONS, AS REVISED JULY 1, 1946

Openhearth and Electric Furnace Alloy Steels
(Blooms, Billets, Slabs, Bars and Bar-Strip)

A.I.S.I. Number*	C	Mn	P Max.†	S Max.†	Si†	Ni	Cr	Mo	1946 S.A.E. Number
A 1320	0.18-0.23	1.60-1.90	0.040	0.040	0.20-0.35	....	....	....	1320
A 1330	0.28-0.33	1.60-1.90	0.040	0.040	0.20-0.35	....	....	....	1330
A 1335	0.33-0.38	1.60-1.90	0.040	0.040	0.20-0.35	....	....	....	1335
A 1340	0.38-0.43	1.60-1.90	0.040	0.040	0.20-0.35	....	....	....	1340
A 2317	0.15-0.20	0.40-0.60	0.040	0.040	0.20-0.35	3.25-3.75	....	....	2315 2317
A 2330	0.28-0.33	0.60-0.80	0.040	0.040	0.20-0.35	3.25-3.75	....	....	2330
A 2335	0.33-0.38	0.60-0.80	0.040	0.040	0.20-0.35	3.25-3.75	....	....	....
A 2340	0.38-0.43	0.70-0.90	0.040	0.040	0.20-0.35	3.25-3.75	....	....	2340
A 2345	0.43-0.48	0.70-0.90	0.040	0.040	0.20-0.35	3.25-3.75	....	....	2345
E 2512	0.09-0.14	0.45-0.60	0.025	0.025	0.20-0.35	4.75-5.25	....	....	....
A 2515	0.12-0.17	0.40-0.60	0.040	0.040	0.20-0.35	4.75-5.25	....	....	2515
E 2517	0.15-0.20	0.45-0.60	0.025	0.025	0.20-0.35	4.75-5.25	....	....	....
A 3115	0.13-0.18	0.40-0.60	0.040	0.040	0.20-0.35	1.10-1.40	0.55-0.75	....	3115
A 3120	0.17-0.22	0.60-0.80	0.040	0.040	0.20-0.35	1.10-1.40	0.55-0.75	....	3120
A 3130	0.28-0.33	0.60-0.80	0.040	0.040	0.20-0.35	1.10-1.40	0.55-0.75	....	3130
A 3135	0.33-0.38	0.60-0.80	0.040	0.040	0.20-0.35	1.10-1.40	0.55-0.75	....	3135
A 3140	0.38-0.43	0.70-0.90	0.040	0.040	0.20-0.35	1.10-1.40	0.55-0.75	....	3140
A 3141	0.38-0.43	0.70-0.90	0.040	0.040	0.20-0.35	1.10-1.40	0.70-0.90	....	X3140 3141
A 3145	0.43-0.48	0.70-0.90	0.040	0.040	0.20-0.35	1.10-1.40	0.70-0.90	....	3145
A 3150	0.48-0.53	0.70-0.90	0.040	0.040	0.20-0.35	1.10-1.40	0.70-0.90	....	3150
(b)	0.38-0.45	0.40-0.60	0.040	0.040	0.20-0.35	1.65-2.00	0.90-1.20	....	3240
E 3310	0.08-0.13	0.45-0.60	0.025	0.025	0.20-0.35	3.25-3.75	1.40-1.75	....	3310 3312
E 3316	0.14-0.19	0.45-0.60	0.025	0.025	0.20-0.35	3.25-3.75	1.40-1.75	....	...
A 4023	0.20-0.25	0.70-0.90	0.040	0.040	0.20-0.35	....	....	0.20-0.30	4023
A 4024	0.20-0.25	0.70-0.90	0.040	(a)	0.20-0.35	....	....	0.20-0.30	....
A 4027	0.25-0.30	0.70-0.90	0.040	0.040	0.20-0.35	....	....	0.20-0.30	4027
A 4028	0.25-0.30	0.70-0.90	0.040	(a)	0.20-0.35	....	....	0.20-0.30	...
A 4032	0.30-0.35	0.70-0.90	0.040	0.040	0.20-0.35	....	....	0.20-0.30	4032
A 4037	0.35-0.40	0.70-0.90	0.040	0.040	0.20-0.35	....	....	0.20-0.30	4037
A 4042	0.40-0.45	0.70-0.90	0.040	0.040	0.20-0.35	....	....	0.20-0.30	4042
A 4047	0.45-0.50	0.70-0.90	0.040	0.040	0.20-0.35	....	....	0.20-0.30	4047
A 4063	0.60-0.67	0.75-1.00	0.040	0.040	0.20-0.35	....	....	0.20-0.30	4063
A 4068	0.64-0.72	0.75-1.00	0.040	0.040	0.20-0.35	....	....	0.20-0.30	4068
(b)	0.17-0.22	0.70-0.90	0.040	0.040	0.20-0.35	....	0.40-0.60	0.20-0.30	4119
(b)	0.23-0.28	0.70-0.90	0.040	0.040	0.20-0.35	....	0.40-0.60	0.20-0.30	4125
A 4130	0.28-0.33	0.40-0.60	0.040	0.040	0.20-0.35	....	0.80-1.10	0.15-0.25	X4130 4130
E 4132	0.30-0.35	0.40-0.60	0.025	0.025	0.20-0.35	....	0.80-1.10	0.18-0.25	....
E 4135	0.33-0.38	0.70-0.90	0.025	0.025	0.20-0.35	....	0.80-1.10	0.18-0.25	....
A 4137	0.35-0.40	0.70-0.90	0.040	0.040	0.20-0.35	....	0.80-1.10	0.15-0.25	4137
E 4137	0.35-0.40	0.70-0.90	0.025	0.025	0.20-0.35	....	0.80-1.10	0.18-0.25	....
A 4140	0.38-0.43	0.75-1.00	0.040	0.040	0.20-0.35	....	0.80-1.10	0.15-0.25	4140
A 4142	0.40-0.45	0.75-1.00	0.040	0.040	0.20-0.35	....	0.80-1.10	0.15-0.25	....
A 4145	0.43-0.48	0.75-1.00	0.040	0.040	0.20-0.35	....	0.80-1.10	0.15-0.25	4145
A 4147	0.45-0.50	0.75-1.00	0.040	0.040	0.20-0.35	....	0.80-1.10	0.15-0.25	....
A 4150	0.48-0.53	0.75-1.00	0.040	0.040	0.20-0.35	....	0.80-1.10	0.15-0.25	4150
A 4317	0.15-0.20	0.45-0.65	0.040	0.040	0.20-0.35	1.65-2.00	0.40-0.60	0.20-0.30	....
A 4320	0.17-0.22	0.45-0.65	0.040	0.040	0.20-0.35	1.65-2.00	0.40-0.60	0.20-0.30	4320
E 4337	0.35-0.40	0.60-0.80	0.025	0.025	0.20-0.35	1.65-2.00	0.70-0.90	0.20-0.30	....
A 4340	0.38-0.43	0.60-0.80	0.040	0.040	0.20-0.35	1.65-2.00	0.70-0.90	0.20-0.30	X4340 4340
E 4340	0.38-0.43	0.60-0.80	0.025	0.025	0.20-0.35	1.65-2.00	0.70-0.90	0.20-0.30	....
A 4608	0.06-0.11	0.40 max.	0.040	0.040	0.25 max	1.40-1.75	....	0.15-0.25	....
A 4615	0.13-0.18	0.45-0.65	0.040	0.040	0.20-0.35	1.65-2.00	....	0.20-0.30	4615
E 4617	0.15-0.20	0.45-0.65	0.025	0.025	0.20-0.35	1.65-2.00	....	0.20-0.27	....
A 4620	0.17-0.22	0.45-0.65	0.040	0.040	0.20-0.35	1.65-2.00	....	0.20-0.30	4620
E 4620	0.17-0.22	0.45-0.65	0.025	0.025	0.20-0.35	1.65-2.00	....	0.20-0.27	....
A 4621	0.18-0.23	0.70-0.90	0.040	0.040	0.20-0.35	1.65-2.00	....	0.20-0.30	....
A 4640	0.38-0.43	0.60-0.80	0.040	0.040	0.20-0.35	1.65-2.00	....	0.20-0.30	4640
E 4640	0.38-0.43	0.60-0.80	0.025	0.025	0.20-0.35	1.65-2.00	....	0.20-0.27	...
A 4812	0.10-0.15	0.40-0.60	0.040	0.040	0.20-0.35	3.25-3.75	....	0.20-0.30	....
A 4815	0.13-0.18	0.40-0.60	0.040	0.040	0.20-0.35	3.25-3.75	....	0.20-0.30	4815
A 4817	0.15-0.20	0.40-0.60	0.040	0.040	0.20-0.35	3.25-3.75	....	0.20-0.30	...
A 4820	0.18-0.23	0.50-0.70	0.040	0.040	0.20-0.35	3.25-3.75	....	0.20-0.30	4820
A 5120	0.17-0.22	0.70-0.90	0.040	0.040	0.20-0.35	....	0.70-0.90	....	5120
A 5130	0.28-0.33	0.70-0.90	0.040	0.040	0.20-0.35	....	0.80-1.10	....	....
A 5140	0.38-0.43	0.70-0.90	0.040	0.040	0.20-0.35	....	0.70-0.90	....	5140
A 5145	0.43-0.48	0.70-0.90	0.040	0.040	0.20-0.35	....	0.70-0.90	....	....
A 5150	0.48-0.53	0.70-0.90	0.040	0.040	0.20-0.35	....	0.70-0.90	....	5150
A 5152	0.48-0.55	0.70-0.90	0.040	0.040	0.20-0.35	....	0.90-1.20	....	....
E 52095	0.95-1.10	0.25-0.45	0.025	0.025	0.20-0.35	....	0.40-0.60	....	50100
E 52098	0.95-1.10	0.25-0.45	0.025	0.025	0.20-0.35	....	0.90-1.15	....	51100
E 52100	0.95-1.10	0.25-0.45	0.025	0.025	0.20-0.35	....	1.20-1.50	....	....
E 52101	0.95-1.10	0.25-0.45	0.025	0.025	0.20-0.35	....	1.30-1.60	....	52100
A 6120	0.17-0.22	0.70-0.90	0.040	0.040	0.20-0.35	....	0.70-0.90	0.10 min. V	...
A 6145	0.43-0.48	0.70-0.90	0.040	0.040	0.20-0.35	....	0.80-1.10	0.15 min. V	....
A 6150	0.48-0.53	0.70-0.90	0.040	0.040	0.20-0.35	....	0.80-1.10	0.15 min. V	6150
E 6150	0.48-0.53	0.70-0.90	0.025	0.025	0.20-0.35	....	0.80-1.10	0.15 min. V	....
A 6152	0.48-0.55	0.70-0.90	0.040	0.040	0.20-0.35	....	0.80-1.10	0.10 min. V	....
A 8615 to A 8660; A 8720 to A 8750; A 9255 to A 9262, See Data Sheet									
E 9310	0.08-0.13	0.45-0.65	0.025	0.025	0.20-0.35	3.00-3.50	1.00-1.40	0.08-0.15	....
E 9315	0.13-0.18	0.45-0.65	0.025	0.025	0.20-0.35	3.00-3.50	1.00-1.40	0.08-0.15	....
E 9317	0.15-0.20	0.45-0.65	0.025	0.025	0.20-0.35	3.00-3.50	1.00-1.40	0.08-0.15	...
A 9437 to A 9445; A 9747 and A 9763; A 9840 to A 9850, See Data Sheet									

*Prefix A means basic openhearth alloy steel; E means electric furnace steel.

†Lowest standard maximum phosphorus or sulphur content for acid openhearth or acid electric furnace alloy steel is 0.05% each; silicon is 0.15% min.

NOTE (a)—Sulphur range: 0.035 to 0.050%.

(b)—Eliminated from A.I.S.I. Standards, as revised July 1, 1946.

TABLE 15–3B

SUPPLEMENTARY STEEL DATA SHEET, AS REVISED JULY 1, 1946

Designation	C	Mn	Si (a)	Ni	Cr	Mo
NICKEL-CHROMIUM-MOLYBDENUM STEELS						
A 8615	0.13–0.18	0.70–0.90	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8617	0.15–0.20	0.70–0.90	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8620	0.18–0.23	0.70–0.90	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8622	0.20–0.25	0.70–0.90	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8625	0.23–0.28	0.70–0.90	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8627	0.25–0.30	0.70–0.90	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8630	0.28–0.33	0.70–0.90	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8632	0.30–0.35	0.70–0.90	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8635	0.33–0.38	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8637	0.35–0.40	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8640	0.38–0.43	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8641	0.38–0.43	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.90	0.15–0.25
A 8642	0.40–0.45	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8645	0.43–0.48	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8647	0.45–0.50	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8650	0.48–0.53	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8655	0.50–0.60	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8660	0.55–0.65	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
A 8720	0.18–0.23	0.70–0.90	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
A 8735	0.33–0.38	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
A 8740	0.38–0.43	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
A 8742	0.40–0.45	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
A 8745	0.43–0.48	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
A 8747	0.45–0.50	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
A 8750	0.48–0.53	0.75–1.00	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
SILICON-MANGANESE AND SILICON-MANGANESE-CHROMIUM STEELS						
A 9255	0.50–0.60	0.70–0.95	1.80–2.20	(c)	(d)	(e)
A 9260	0.55–0.65	0.70–1.00	1.80–2.20	(c)	(d)	(e)
A 9261	0.55–0.65	0.75–1.00	1.80–2.20	(c)	0.10–0.25	(e)
A 9262	0.55–0.65	0.75–1.00	1.80–2.20	(c)	0.25–0.40	(e)
MANGANESE-NICKEL-CHROMIUM-MOLYBDENUM STEELS (H)						
A 9437	0.35–0.40	0.90–1.20	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15
A 9440	0.38–0.43	0.90–1.20	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15
A 9442	0.40–0.45	1.00–1.30	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15
A 9445	0.43–0.48	1.00–1.30	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15
NICKEL-MOLYBDENUM STEELS (J)						
A 9747	0.45–0.50	0.50–0.80	0.20–0.35	0.40–0.70	0.10–0.25	0.15–0.25
A 9763	0.60–0.67	0.50–0.80	0.20–0.35	0.40–0.70	0.10–0.25	0.15–0.25
NICKEL-CHROMIUM-MOLYBDENUM STEELS (K)						
A 9840 (i)	0.38–0.43	0.70–0.90	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30
A 9845 (i)	0.43–0.48	0.70–0.90	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30
A 9850 (i)	0.48–0.53	0.70–0.90	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30

QUESTIONS AND PROBLEMS

1. Name four methods by which steels may be classified.
2. What is the basis of the classification of steels by the numerical system?
3. Identify the following SAE steels: 3140, 4140, 6195, 1020.
4. Give reasons for the continued adoption of some of the NE steels.

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TERMS

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GLOSSARY OF METALLURGICAL TERMS

Acid bottom and lining.—The inner bottom and lining of a melting furnace composed of materials having an acid reaction. The materials may be sand, siliceous rock, or silica bricks.

Acid steel.—Steel melted under a slag which has an acid reaction and in a furnace with an acid bottom and lining.

Aging.—The term originally applied to the process, or sometimes to the effects, of allowing a metal to remain at ordinary temperatures. Heat treatment at temperatures above normal, to accelerate changes of the type that might take place on aging at ordinary temperature, is called "artificial aging," and sometimes merely "aging." When the changes taking place during artificial aging are due to the precipitation of some substance from solid solution, the heat treatment may be called "precipitation treatment."

Alloy.—A material having metallic properties and consisting of two or more elements, of which at least one is a metal. It is considered by some that the elements must be completely miscible in the liquid state; others apply the term alloy even when liquid miscibility is only partial.

Alpha iron.—Iron carbon alloy, in which the ferrite has a body-centered cubic lattice.

Amorphous.—Noncrystalline.

Annealing.—A heating and cooling operation of a material in the solid state. Annealing usually implies a relatively slow cooling.

Austenite.—Face-centered gamma iron in which the maximum solubility of carbon reaches 1.70 per cent at 2066F and decreases to 0.83 per cent at 1330F.

Banded structure.—A segregated structure of parallel bands which run in the direction of working.

Basic bottom and lining.—The inner lining and bottom of a melting furnace composed of materials having a basic reaction. The materials may be crushed and burnt dolomite, magnesite, magnesite bricks, or basic slag.

Basic steel.—Steel melted under a slag having a basic reaction and in a furnace with a basic bottom and lining.

Bessemer process.—A process for making steel by blowing air through molten iron contained in a suitable vessel, thus removing the impurities.

Billet.—A semifinished rolled ingot of rectangular cross-section or nearly so. In general, the term "billet" is used when the cross-section ranges from 4 up to 36 sq. in., the width always being less than twice the thickness. Small sizes are usually classed as bars or "small billets." The term "bloom" is properly used when the cross-section is greater than about 36 sq. in., but this distinction is not universally observed.

Binary alloy.—An alloy containing two principal elements.

Black annealing.—A process of annealing sheets, prior to tinning, in boxes which impart a black color to the surface of the product. The term is also used in the manufacture of other products when no special precautions are needed to insure that the annealed product is free from scale or discoloration.

Blast furnace.—A shaft furnace supplied with air blast, usually hot, for producing pig iron by melting iron ore. The furnace is continuous in operation, the raw materials (iron ore, coke, and limestone) are charged at the top, and the molten iron and slag are collected at the bottom and are tapped out at intervals.

Blister.—A defect in metal produced by gas bubbles either on the surface or formed beneath the surface while the metal is hot or plastic. Very fine blisters are called pinhead or pepper blisters.

Bloom.—See *Billet.*

Blowhole.—A hole produced during the solidification of metal by evolved gas which, in failing to escape, is held in little pockets.

Blue annealing.—A process of annealing sheets after rolling. The sheets, if fairly heavy, are allowed to cool slowly after the hot rolling; if of lighter gauge, as is usually the case, they are passed singly through an open furnace where they are heated to the proper temperature for the annealing operation. As the name indicates, they have a bluish-black appearance.

Blue brittleness.—Brittleness occurring in steel when in the temperature range of 400–700F, or when cold after being worked within this temperature range.

Box annealing.—Softening steel by heating it in a suitable closed metal box or pot to protect it from oxidation; also called close annealing or pot annealing.

Bright annealed wire.—Wire carefully annealed in closed pots, often with reducing gases, to keep surface oxidation to a minimum.

Carbon steel.—Steel which owes its properties chiefly to various percentages of carbon without substantial amounts of other alloying elements; also known as ordinary steel or straight carbon steel.

Carburizing (cementation).—Adding carbon to iron-base alloys by heating the metal below its melting point in contact with carbonaceous solids, liquids, or gases. *Note:* The term "carbonizing" used in this sense is incorrect so its use should be discouraged.

Case.—That portion of a carburized, nitrided, or cyanided iron-base alloy article in which the carbon or nitrogen content has been substantially increased. *Note:* Also refers to both casehardening and carburizing.

Casehardening.—Carburizing, and subsequent hardening by suitable heat treatment, all or part of the surface portions of a piece of iron-base alloy.

Casting.—Any object made by pouring molten metal into molds or dies.

Casting strains.—Strains accompanied by internal stresses resulting from the cooling of a casting.

Cementite.—Iron carbon compound corresponding to the symbol Fe_3C.

Chill cast pig.—Pig iron cast into metal molds or chills. If a machine is used, the product is known as machine cast pig.

Cleavage plane.—The planes of easy rupture or slippage in crystals.

Cogging.—Rolling or forging ingots to reduce them to blooms.

Cold-rolling.—See *Cold-working.*

Cold shut.—(1) A portion of the surface of a metal product which is not integral with the main mass. This usually results from rolling or forging into the product a separate or partially separate piece of metal, such as that which spatters on the surface of an ingot, or mechanical projections. (2) The freezing over of the top surface of an ingot before the mold has been filled, due to an interruption of the stream of metal.

Cold-working.—Permanent deformation of a metal below its recrystallization temperature.

Combined carbon.—All of the carbon in iron or steel which is not in the form of graphite.

Core.—That portion of a carburized iron-base alloy article in which the carbon content has not been substantially increased. *Note:* Also refers to both casehardening and carburizing. The word "core" is sometimes used to indicate the inner part of a billet or bar rolled from rimmed steel to differentiate it from the rimmed portion or rim. Also a body of sand or other material placed in a mold to produce a cavity in a casting.

Cored structure.—A structure having its interior or core of different structure or material from the exterior.

Critical points.—Transformation temperatures of metals designated on the iron carbon diagram as A_1, A_2, A_3.

Critical range.—Temperature range between various critical points.

Cyaniding.—Surface-hardening of an iron-base alloy article or portion of it by heating at a suitable temperature in contact with a cyanide salt, followed by quenching.

Decarburization.—The removal of carbon (usually refers to the surface of solid steel).

Dendrite.—A crystal formed during solidification, having many branches and a tree-like pattern; also termed "pine tree" and "fir tree" crystals.

Differential heating.—Heating conducted in such a way that various portions of an object attain different temperatures so that, upon cooling, different properties are produced.

Dissolved carbon.—Carbon in solution in either the liquid or solid state.

Elastic limit.—The greatest load per square inch of the original cross-sectional area which, when removed, has not caused a permanent elongation exceeding 0.0001 in. per in. of gauge length.

Elongation.—The amount of permanent stretch, before rupture; usually expressed as percentage of the original length, such as 25 per cent in 2 in.

Endurance limit.—The maximum stress to which material may be subject an indefinitely large number of times without causing failure.

Eutectic.—An alloy having the lowest melting point possible with the given components.

Eutectoid steel.—A steel of the eutectoid composition. In plain carbon steel this composition is considered to be about 0.83 per cent carbon. Composition S on the iron carbon diagram. In alloy steels the carbon content may be considerably lower.

Fatigue.—Used incorrectly to explain the phenomenon of the progressive fracture of a metal by means of a crack which progresses under repeated stress.

Ferrite.—Alpha iron in which is held in solid solution a maximum amount of 0.035 per cent carbon at 1330F, which decreases to about 0.008 per cent at room temperature.

Ferro-alloys.—An alloy of iron with a sufficient amount of some element or elements, such as manganese, chromium, or vanadium, used as a means of introducing these elements into steel.

Fiber.—A characteristic of wrought metal manifested by a fibrous or woody appearance of fractures and indicating directional properties. Fiber is due chiefly to the extension in the direction of working of the constituents of the metal, both metallic and nonmetallic.

Finishing temperature.—The temperature at which hot mechanical working of metal is completed.

Flash.—A thin fin of metal formed at the sides of a forging where a small portion of the metal is forced out between the edges of the forging dies.

Forging strains.—Strains resulting from forging or from cooling from the forging temperature.

Fusible alloys.—A group of nonferrous alloys which melt at very low temperatures. They usually consist of bismuth, lead, and tin in various proportions, and iron only as an impurity.

Gamma iron.—A crystal form of iron (face-centered cubic) stable between A_3 and A_4.

Grain growth.—An increase in the grain size of metal.

Grains.—Aggregates formed by the coalescence of crystals.

Granular pearlite (also globular pearlite and divorced pearlite).—A structure formed from the pearlite phase by long annealing of steel or at a temperature just below the lower critical point, causing the cementite to spheroidize in a ferrite matrix. Since "pearlite" connotes a lamellar structure, this name is not recommended; the word "spheroidite" has been proposed.

Hardening.—Heating and quenching certain iron-base alloys from a temperature either within or above the critical temperature range.

Hot shortness.—Brittleness in metal when hot.

Hot-working.—The mechanical working of metal above the recrystallization temperature.

Hypereutectoid steel.—A steel containing more than the eutectoid percentage of carbon. See *Eutectoid steel.*

Hypoeutectoid steel.—A steel containing less than the eutectoid percentage of carbon; also see *Eutectoid steel.*

Impact test.—A test in which one or more blows are suddenly applied to a specimen. The results are usually expressed in terms of energy absorbed or number of blows (of a given intensity) required to break the specimen.

Inclusions.—Particles of slag and dirt occurring in metal, which were mechanically held during solidification.

Ingot.—A special kind of casting for subsequent rolling or forging.

Killed steel (also dead).—Molten steel which has been held in a ladle, furnace, or crucible (and usually treated with aluminum, silicon, or manganese) until no more gas is evolved and the metal is perfectly quiet.

Lap weld.—In making some tubes or pipe, the edges of the skelp are beveled or scarfed so that, when they are overlapped, they can be welded together. The product is known as lap weld or lap welded pipe.

Ledeburite.—The carbide-austenite eutectic forming at point C on the iron carbon diagram. During cooling, the austenite in ledeburite transforms to ferrite and carbide. It is found in cast-iron and high-alloy steels, such as high-speed steel.

Macroscopic.—Visible either with the naked eye or under low magnifications (up to about 10 diameters).

Macrostructure.—The structure and internal condition of metals as revealed on a ground or polished (and sometimes etched) sample, by either the naked eye or under low magnifications (up to about 10 diameters).

Martensite.—A structure of quenched steel characterized by an acicular or needlelike pattern. It has the maximum hardness of any of the decomposition products of austenite.

Matrix.—The ground mass or principal substance in which a constituent is embedded.

Mechanical working.—Subjecting metal to pressure exerted by rolls, presses, or hammers in order to change its form or to affect the structure and therefore the physical properties.

Modulus of elasticity.—The ratio, within the limits of elasticity, of the stress to the corresponding strain. The stress in pounds per square inch is divided by the elongation in fractions of an inch for each inch of the original gauge length of the specimen.

Network structure.—A structure in which the grains or crystals of one constituent are partially or entirely surrounded with envelopes of another constituent. The appearance of an etched section through the crystals is that of network.

Neumann bands.—Parallel lines or narrow bands running across crystalline grains of metal. The lines or bands undoubtedly indicate mechanical twins. Neumann bands are generally produced by a sudden deformation of the metal such as would result from shock, impact, or explosion.

Nitriding.—Adding nitrogen to iron-base alloys by heating the metal in contact with ammonia gas or other suitable nitrogenous material. *Note:* Nitriding is conducted at a temperature below the iron carbon critical temperature range and produces surface hardening of the metal without quenching.

Overheating.—Heating to such high temperatures that the grains have become coarse, thus impairing the properties of the metal.

Pearlite.—The lamellar aggregate of ferrite and carbide resulting from the direct transformation of austenite at Ar_1. *Note:* It is recommended that this word be reserved for microstructures consisting of thin plates or lamellae—that is, those that may have a pearly luster in white light. The lamellae can be very thin and resolvable only with the best microscopic equipment and technique, which fact has caused many fine pearlites to be erroneously called "troostite" or "sorbite."

Permanent mold.—A metal mold which is used repeatedly for the production of many castings of the same form. Not commonly applied to ingot molds.

Piercing.—Producing a hole in metal by forcing a pointed tool through it. Usually refers to making steel tubes from solid steel bars.

Pipe.—A cavity formed in metal (especially ingots) during the solidification of the last portion of liquid metal. Contraction of the metal causes this cavity or pipe.

Red shortness.—Brittleness in steel when it is red hot.

Reduction of area.—The difference between the original cross-sectional area and that of the smallest area at the point of rupture. It is usually stated as a percentage of the original area; also called "contraction of area."

Regenerative quenching.—A double quenching of carburized objects to refine the case and core. The first quench is from a high temperature to refine the core, and the second quench is from a lower temperature to further refine the core and harden the case.

Rimmed steel.—A low-carbon steel which (a) is effervescent when cast and during a considerable part of its solidification; (b) neither rises nor falls in the mold to any marked extent; (c) when completely solidified has no pipe but blowholes, both centrally located and deep-seated below the surface; (d) has been cleansed from some of the impurities and dirt because of their rising to the top during the agitation of the molten metal by the escaping gases; and (e) has a cross-section divided into three fairly well defined zones: (1) a very clean thin outer layer of nearly the same chemical composition as when poured; (2) a central portion; and (3) an intermediate portion. The three zones are positively and negatively segregated with respect to metalloids. *Note:* The term "rimmed" comes from the fact that during the gradual freezing inwards from the sides the molten portion at the top of the ingot becomes smaller and smaller and is said to "rim in" until finally the whole top is solidified.

Scab (scabby).—A rough projection on a casting caused by the mold breaking or being washed by the molten metal; or occurring where the skin from a blowhole has partly burned away and is not welded.

Seam.—A crack on the surface of metal which has been closed but not welded; usually produced by blowholes which have become oxidized. If very fine, a seam may be called a hair crack or hair seam; also see *Cold shut.*

Self hardening steel.—Alloy tool steel that becomes sufficiently hard by cooling in air (sometimes an air blast is employed) and whose cutting edges remain practically intact at temperatures approaching a visible red.

Sinkhead or hot top.—A heat-insulated reservoir for excess metal on top of an ingot mold which feeds the shrinkage of the ingot proper.

Skelp.—A plate of steel or wrought iron from which pipe or tubing is made. This is done by rolling the skelp up longitudinally into shape and welding or riveting the edges together.

Slip bands.—A series of parallel lines running across a crystalline grain. Slip bands are formed when the elastic limit is passed by one layer or portion of the crystal slipping over another portion along a plane, known as the slip plane.

Soaking.—Holding steel at temperature for a sufficient time to allow complete and uniform penetration of the heat.

Solidification range.—The temperature range through which metal freezes or solidifies.

Solidus.—The lower line of a fusibility curve, below which the metal is entirely solid.

Sorbite.—A late stage in the tempering of martensite, when the carbide particles have grown so that the structure has a distinctly granular appearance. Further and higher tempering causes globular carbides to appear clearly. *Note:* Many times the term sorbite is erroneously given to an imperfectly developed pearlite or mixed structure in steel.

Spheroidal or spheroidized cementite.—The product of long annealing of unhardened steel (spheroidizing anneal) near but below its transformation range, whereby the carbide lamellae in pearlite areas ball up into small globules in the ferrite matrix. The same structure is achieved by long, high tempering of hardening steel. *Note:* The term "spheroidized pearlite" should be avoided, when the structure is undoubtedly the result of spheroidizing anneal of a pearlitic steel. The term "spheroidite" has been proposed.

Tapping.—Removing molten steel from the melting furnace by opening the taphole and allowing the steel to run out into the ladle.

Teeming.—Pouring molten steel or iron from the ladle into ingot molds.

Temper carbon.—A form of graphite in iron-base alloys produced by heating below the melting point.

Ternary alloy.—An alloy containing three principal elements.

Troostite.—A microconstituent of hardened or hardened and tempered steel which etches rapidly and, therefore, usually appears dark. It consists of a very fine aggregate of ferrite and cementite and is not resolved. *Note:* Two entirely different structures are frequently confused and called troostite. Since the nodular, quick etching microconstituent, which is found in steels that are cooled slightly too slowly to be fully martensitic, can be resolved into very fine pearlite, it is recommended that the use of the term "troostite" or "quenching troostite" or "nodular troostite" to denote this structure be avoided. "Temper troostite" is the first product of the tempering of martensite and consists of submicroscopic particles of carbide in ferrite, and is frequently indistinguishable in general appearance from a quickly etching martensite. If the word troostite is to be retained it should be reserved for this. It changes on higher tempering by indistinguishable degrees into sorbite.

Twin crystals.—Crystalline grains or parts of grains, which are symmetrical structurally with respect to a plane between them called the twinning plane. Usually if either part of the twin were revolved a certain amount about an axis perpendicular to the twinning plane, the two parts would possess the same orientation.

Widmanstatten structure.—When the austenite in low-carbon steel transforms to ferrite and pearlite in such a manner as to produce marked precipitation of the ferrite at the crystallographic planes so that the ferrite appears as long continuous plates which occur in definite directions in each grain, the structure is referred to as the Widmanstatten structure. The term is sometimes applied to similar structures in other alloys.

Work hardness.—Hardness developed in metal resulting from mechanical-working, particularly cold-working.

GLOSSARY OF FOUNDRY TERMS

Airdried.—Refers to a core that has dried or partially dried in the air before being baked in an oven.

Air furnace.—A furnace for melting iron for malleable-iron castings.

Anchor.—Appliance used to hold cores in place in molds.

Arbor.—A bar or mandrel on which a core is built up.

Bars.—Ribs placed across the cope of a flask.

Bed charge.—The first coke charged into the cupola.

Bedding in.—Sinking a pattern into the sand.

Bellows.—A tool used to blow loose sand from the mold.

Bench molding.—Making molds on the bench.

Binder.—Material used to hold sand together.

Blast.—A current of air blown into the cupola by blower or fan.

Bott.—The chunk of clay stuck on the end of a stopping bar and used to stop the flow of metal from the cupola.

Bottom board.—The board that the mold rests on.

Breast.—The clay put into the opening, above the spout of the cupola, to form the tap hole.

Bull ladle.—A two-man ladle used for carrying and pouring metal.

Butt-ramming.—Ramming with the large, round end of the rammer.

Casting.—The metal shape that is obtained as a result of pouring metal into a mold.

Chaplet.—A metal support used to hold a core in place in a mold.

Cheek.—The portion of a flask placed between the cope and drag.

Chill.—Iron placed against the pattern to make a hard surface on the casting.

Chilled casting.—A casting that was cooled very rapidly.

Chuck.—A small bar set between crossbars to secure sand in the cope.

Churning.—Feeding molten metal into a casting with an iron rod when the metal is solidifying.

Cinder bed.—A layer of cinders or coke placed beneath a mold.

Clamping bar.—A bar used to clamp molds.

Clay wash.—Clay thinned with water and used as a coating for gaggers and the inside of flasks.

Contraction.—Decrease in size of casting due to cooling.

Cope.—The upper part of a flask or mold.

Core.—A body of sand used to form holes or openings through castings.

Core box.—A box in which a core is formed.

Core drier.—A form which holds the core in shape while it is baking.

Core oven.—An oven in which cores are baked.

Core plate.—An iron plate used to hold the core after it is made.

Core print.—A projection on a pattern which forms in the sand an impression used in locating a core and in holding it in place when the mold is poured.

Core wash.—A blackening mixture with which cores are painted.

Crushing.—The pushing out of shape of core or mold, when two parts of the mold that do not fit properly meet.

Cupola.—A furnace used for melting iron.

Daubing.—Filling cracks in cores or plastering a cupola after the heat.

Draft.—The taper given to a pattern to enable it to be drawn from the sand.

Drag.—The bottom part of a flask or mold.

Draw peg.—A wooden peg used for drawing patterns.

Draw plate.—A plate put into the pattern to be used for drawing the pattern from the sand.

Dropout.—The falling away of sand from the cope when the mold is closed.

Dry-sand mold.—A mold made while the sand is damp but baked in an oven before it is poured.

Dull iron.—Iron not so hot as it should be for best pouring.

Facing.—A material put next to the pattern when making a mold.

False cheek.—A cheek used in making a three-part mold in a two-part flask.

Feeding.—Pouring metal into the feeder while the casting is solidifying.

Fin.—Metal on a casting that has run into an imperfect joint in the mold.

Floor molding.—Making molds on the foundry floor.

Flow-off gate.—An opening through which the metal flows after the mold is filled.

Flux.—A fusible material, such as limestone, charged into the cupola to assist in purifying the molten metal and to thin the slag.

Follow board.—A board in which the pattern lies to the parting line.

Frozen iron.—Iron which has solidified.

Gaggers.—Metal supports especially made to reinforce the sand in the cope.

Green core.—A core that has not been baked.

Green ladle.—A ladle with a lining that is not dry.

Green sand.—Sand that is in a damp state.

Green-sand core.—A core made of green sand.

Hand ladle.—A small ladle carried by one man.

Heat.—The melting time of the metal in the cupola.

Hot metal.—Metal hot enough to flow easily.

Jarring machine.—A molding machine that packs the sand by jarring.

Joint.—The part of the mold where the cope and cheek, cope and drag, or cheek and drag come together.

Loam.—A mixture of sand and clay used in loam molding.

Loam mold.—A mold built up of brick, covered with a loam mud, and then baked before being poured.

Malleable casting.—A casting made of white iron and then heat-treated or annealed.

Match plate.—A plate to which the patterns are fastened at the parting line.

Melting zone.—The portion of the cupola above the tuyeres, where most of the metal melts.

Molding board.—The board on which the pattern is placed when beginning the mold.

New sand.—Sand that has not been used for molding.

Old sand.—Common heap sand that has been used for molding.

Peeling.—The ready dropping away of sand from the casting.

Peen-ramming.—Ramming with the wedge end of the rammer.

Pit molding.—Making molds in pits in the foundry floor.

Pouring basin.—A basin in the cope into which the metal is poured and from which it runs into the mold.

Rapping.—Jarring the pattern to loosen it before drawing it from the sand.

Riddle.—A sieve used for sifting sand.

Riser.—An opening in the cope into which the metal rises when the mold is filled; also, that part of the casting formed in the opening.

Runner box.—A frame placed on the cope for making the pouring basin.

Scabs.—Rough surfaces on castings due to portions of the surface of the mold giving away.

Sea coal.—A bituminous coal finely ground.

Set-off box.—A box used to set the cope on when it is lifted from the drag.

Shot iron.—Small pieces of iron obtained from the cupola dump.

Skim gate.—A gate so arranged as to skim any impurities from the surface of the metal when the mold is poured.

Skimmer.—A piece of iron used to prevent the dirt floating on top of the metal from entering the mold.

Skin drying.—Drying the surface of a green-sand mold.

Slag.—A material run out of the cupola through the slag hole.

Slag hole.—A hole in the back of the cupola through which the slag is drawn.

Slip jacket.—A frame to place around a snap-flask mold after the flask is removed.

Snap flask.—A hinged flask that is removed from the mold after the mold is made.

Soldiers.—Wooden blocks or sticks used to reinforce bodies of sand in the cope.

Spongy castings.—Castings in which the iron is very open grained.

Spout.—A trough through which the metal flows from the cupola to the ladle.

Sprue hole.—The opening through which the metal is poured into the cope to run the casting.

Swab.—A sponge or piece of waste used to wet the sand around the pattern before drawing it from the sand.

Sweep work.—Molds made of pieces of patterns and sweeps instead of patterns.

Tap hole.—The opening in the furnace through which the metal is drawn from the furnace.

Tuyeres.—The openings in the cupola through which the air passes from the windbox into the cupola.

Upset.—A frame used to deepen either the cope or drag.

Vent.—A small opening made in the mold for the escape of gases when the mold is poured.

Weak sand.—Sand that will not hold together when the mold is made.

GLOSSARY OF FORGING TERMS

Coining.—Forming, to close tolerances, of a part of a metal surface by applying pressure over a small area.

Drawing out.—Lengthening stock under impact or pressure.

Drop-forging.—Forming metal by impact of falling hammer. Both hammer and anvil are usually fitted with special dies. Forming may take place in succeeding steps, with several recesses cut in the same dies.

Edging.—Forming the ends of bar stock or similar stock, usually with the aid of dies.

Embossing.—Forcing into relief of a metal surface.

Extruding.—Metal forced through die which forms it continuously and uniform in cross-section.

Forge-welding.—Uniting of two or more pieces of metal by heating to incipient fusion and forcing together; a flux is applied to eliminate oxide film.

Forming.—Pressing metal into shape, usually with the aid of forms or dies.

Fullering.—Forming bar stock or similar stock between the ends.

Heavy forging.—Working down of ingots or large billets.

Hot-cutting.—Cutting off excess stock with the hot chisel or slice bar.

Ironing.—Imparting a high finish to work by squeezing between smooth dies.

Piercing.—Hollowing out large stock by driving a mandrel or pointed arbor into it or through it.

Planishing.—Smoothing and truing work by repeated blows or squeezings between smooth dies.

Punching.—Piercing of thin stock by a shaped tool, which is held in the machine or is forced through the stock by a power hammer.

Shearing.—Parting of metal, usually cold, between sharpened blades.

Straightening.—Aligning of semifinished parts distorted by processing.

Swaging.—Marking or shaping surface of stock by working between dies.

Trimming.—Cutting away excess metal, as flashing from drop-forgings.

Upsetting.—Building up metal at some point by shortening the piece through axial compression.

GLOSSARY OF WELDING TERMS

(Definitions Furnished by American Welding Society)

Actual throat.—The perpendicular distance from the hypotenuse to the right angle of the largest right isosceles triangle that can be inscribed in a fillet weld.

Alternating-current arc welding.—An arc welding process wherein the power supply at the arc is alternating current.

Arc-stream voltage.—The voltage across the gaseous zone which varies with the length of the arc.

Arc welding.—A nonpressure (fusion) welding process, wherein the welding heat is obtained from an electric arc formed either between the base metal and an electrode, or between two electrodes.

Atomic hydrogen welding.—An alternating-current arc welding process, wherein the welding heat is obtained from an arc produced between two suitable electrodes in an atmosphere of hydrogen.

Automatic welding.—Welding with equipment which automatically controls the entire welding operation (including feed, speed, oscillation, interruption, etc.).

Backfire.—The re-ignition of the gases in a gas welding or cutting torch tip after the flame has been extinguished by a momentary receding of the flame into the tip.

Backhand welding.—A gas welding technique, wherein the flame is directed on the deposited metal and the unwelded groove, in the direction opposite to the progress of welding.

Backing strip.—Material (metal, asbestos, carbon, etc.) backing up the root of the weld.

Back-step welding.—A welding technique wherein the increments of weld metal are deposited opposite to the direction of progression.

Bare electrode (lightly coated).—A solid metal electrode with no coating other than that incidental to the manufacture of the electrode, or with a light coating.

Base metal (parent metal).—The metal to be welded, or cut.

Base metal test specimen.—A test specimen composed wholly of base metal.

Bead weld.—A type of weld made by one passage of electrode or rod.

Brazing.—A group of welding processes wherein the filler metal is a nonferrous metal or alloy whose melting point is higher than 1000F but is lower than that of the metals or alloys to be joined.

Carbon arc cutting.—The process of severing metals by melting with the heat of the carbon arc.

Carbon arc welding.—An arc welding process wherein a carbon or graphite electrode is used, with or without the use of filler metal.

Carburizing flame (carbonizing).—A gas flame having the property of introducing carbon into the metal heated.

Chemical dip-brazing.—A dip-brazing process, wherein the filler metal is added to the joint before immersion in a bath of molten chemicals.

Cone.—The conical part of a gas flame which is next to the orifice of the tip.

Covered (shielded arc) electrode.—A metal electrode which has a relatively thick covering material serving the dual purpose of stabilizing the arc and improving the properties of the weld metal.

Crater.—A depression at the termination of an arc weld.

Cutting tip (nozzle).—A gas torch tip especially adapted for cutting.

Cutting torch or blowpipe.—A device used in gas cutting for controlling the gases used for preheating and the oxygen used for severing the metal.

Deposited metal.—Metal that has been added by a welding process.

Depth of fusion.—The depth of fusion of a groove weld is the distance from the original surface of the base metal to that point within the joint at which fusion ceases.

Direct-current arc welding.—An arc welding process, wherein the power supply at the arc is direct current.

Electrode holder.—A device used for mechanically holding the electrode.

Filler metal.—Material to be added in making a weld. A glass used in goggles, helmets, and shields to exclude harmful light rays.

Flashback.—A receding of the flame into or back of the mixing chamber of the torch.

Flash-butt welding.—A resistance butt welding process, where the potential is applied before the parts are brought in contact and where the heat is derived principally from a series of arcs between the parts being welded.

Flash (fin).—Metal expelled from a joint made by the resistance welding process.

Flush weld.—A weld made with a minimum reinforcement.

Flux.—A fusible material or gas used to: dissolve and/or prevent the formation of oxides, nitrides, or other undesirable inclusions formed in welding; assist in purifying molten metal; or increase fluidity of slag.

Forehand welding.—A gas welding technique, wherein the flame is directed on the deposited metal and the unwelded groove, in the direction of the progress of welding.

Free bend test specimen.—A bending test, wherein the specimen is bent without constraint of a jig.

Fusion welding.—A group of welding processes in which metals brought to the molten state at the surfaces to be joined are welded with or without the addition of filler metal and without the application of mechanical pressure or blows.

Gas cutting.—The process of severing ferrous metals by means of the chemical action of oxygen on elements in the base metal.

Gas pocket (blowhole).—A cavity in a weld caused by gas inclusion.

Gas welding.—A nonpressure (fusion) welding process, wherein the welding heat is obtained from a gas flame.

Guided bend test.—A bending test, wherein the specimen is bent to a definite shape by means of a jig.

Heat-affected zone.—The portion of the base metal whose structure or properties have been altered by the heat of welding.

Induction brazing.—An electric brazing process, wherein the heat is obtained from induced current.

Interrupted spot welding.—A spot welding process, wherein fusion is accomplished by means of successive applications of electrical energy between contact electrodes during a single application of pressure to the electrodes.

Kerf.—The space from which the metal has been removed by a cutting process.

Manual weld.—A weld made by an operator unaided by mechanically or electrically controlled equipment.

Melting rate.—The weight of electrode consumed in a unit of time.

Mixing chamber.—That part of a gas welding or cutting torch, wherein the gases are mixed for combustion.

Multiple resistance welding.—A resistance welding process, wherein two or more separate welds are made simultaneously.

Neutral flame.—A gas welding flame, wherein the portion used is neither oxidizing nor reducing.

Nonpressure welding.—A group of welding processes, wherein the weld is made without pressure.

Oxidizing flame.—A gas welding flame, wherein the portion used has an oxidizing effect.

Oxyacetylene welding.—A gas welding process, wherein the welding heat is obtained from the combustion of oxygen and acetylene.

Peening.—Mechanical working of metal by means of hammer blows.

Penetration.—Depth of fusion.

Percussive welding.—A resistance welding process utilizing stored-up electrical energy suddenly discharged.

Porosity.—A multiplicity of gas pockets or inclusions.

Postheating.—Heat applied to base metal subsequent to welding or cutting.

Preheating.—Heat applied to base metal prior to welding or cutting.

Pressure welding.—A group of welding processes, wherein the weld is consummated by pressure.

Progressive spot welding.—A resistance spot welding process, wherein two or more spot welds are made automatically, one after the other, by the actuation of a single control device.

Projection welding.—A resistance welding process, wherein localization of heat between two surfaces or between the end of one member and surface of another is effected by projections.

Reducing flame.—A gas welding flame, wherein the portion used has a reducing effect.

Residual stress.—Stresses remaining in a structure or member as a result of thermal or mechanical treatment, or both.

Resistance brazing.—An electric brazing process, wherein the heat is obtained from the resistance to the flow of an electric current.

Resistance butt welding.—A group of resistance welding processes, wherein the fusion occurs simultaneously over the entire contact area of the parts being joined.

Resistance welding.—A pressure welding process, wherein the heat is obtained from the resistance to the flow of an electric current.

Reversed polarity.—The arrangement of arc welding loads, wherein the work is the negative pole and the electrode is the positive pole in the arc circuit.

Seal weld (seal bead).—A weld used to obtain tightness.

Seam welding.—A resistance welding process, wherein overlapping or tangent spot welds are made progressively.

Shielded carbon arc welding.—A carbon arc welding process, wherein the arc and molten weld metal are protected from the atmosphere by a shielding medium.

Shielded metal arc welding.—A metal arc welding process, wherein the arc and weld metal are protected from the atmosphere by a shielding medium.

Slag inclusion.—Nonmetallic material entrapped in a weld. The difference in weight between the amount of electrode deposited and the weight of the electrode consumed (melted).

Spot welding.—A resistance welding process, wherein the fusion is confined to a relatively small portion of the area of the lapped parts to be joined.

Straight polarity.—The arrangement of arc welding leads, wherein the work is the positive pole and the electrode is the negative pole of the arc circuit.

Stress relief heat treatment.—Uniform heating of structures to a sufficient temperature below the critical range, to relieve the major portion of the residual stresses, followed by uniform cooling.

Tack weld.—A weld used for assembly purposes only.

Thermit crucible.—A vessel in which the thermit reaction takes place.

Thermit mixture.—A mixture of plain thermit and other alloying metals.

Thermit reaction.—A chemical reaction between iron oxide and aluminum which produces a highly superheated liquid iron and aluminum oxide slag.

Thermit welding.—A nonpressure (fusion) welding process, wherein the heat is obtained from liquid steel produced by a thermit reaction, and the filler metal is supplied by the steel produced in this reaction.

Undercut.—Gouging away of metal at the boundary of the weld metal with the parent metal.

Upset butt welding.—A resistance butt welding process, wherein the potential is applied after the parts to be welded are brought in contact and where the heat is derived principally from resistance.

Weaving.—A technique of depositing weld metal, in which the electrode is oscillated at right angles to direction of travel.

Weld.—A localized consolidation of metals by a welding process.

Weldment.—An assembly whose component parts are joined by welding.

Weld metal.—The metal resulting from the fusion of the filler and base metals.

Welding pressure.—External force applied in the pressure welding processes to control the current density throughout the weld, or effects of fusion or both.

Welding rod.—Filler metal, in wire or rod form, used in the gas welding process and those arc welding processes where the electrode does not furnish the metal.

Welding tip.—A gas torch tip especially adapted for welding.

Welding torch or blowpipe.—A device used in gas welding for mixing and controlling the gases.

ALUMINUM ALLOYS

Compositions, Properties, and Designations of American Commercial Alloys

Compiled by H. S. Jerabek, University of Minnesota, from Handbooks and Specifications of American Society for Metals, American Society for Testing Materials, Society of Automotive Engineers, & Aluminum Co. of America

Wrought Alloys

Designations			Composition (Aluminum = Balance)					Form Tested	Tensile(b) Strength, 1000 Psi.		Yield(b) Strength, 1000 Psi.		Elong., % in 2 In.		Brinell Hardness	Shear Str.(b) 1000 Psi.	Endur. Limit(c) 1000 Psi.	Cold Bend Test(d)	Corrosion Resistance in NaCl(e)	Alcoa No.	Characteristics and Uses
S.A.E. No.	A.S.T.M. Specification	Alcoa No.(a)	Cu	Si	Mn	Mg			Ave.	Min.	Ave.	Min.	Ave.	Min.							
									Work Hardening Alloys(f)												
25	B25-41T	2s O					99 Al	1/16" Sheet	13	(15.5 max.)	5		35	30	23	9.5	5	A	B	2s O	Commercial Al; Good Forming Properties Good Corrosion Resistance, Low Yield Str. Cooking Utensils, Sheet and Tubing
	B25-41T	2s ½H						. .	17	16	14		9	7	32	11		B	B	2s ½H	
	B25-41T	2s H						. .	24	22	21		5	4	44	13	8.5	F	B	2s H	
29	B79-41T	3s O			1.2			. .	16	(19 max.)	5		30	25	28	11	6	A	B	3s O	Similar to 25 Slightly Stronger and Less Ductile Cooking Utensils, Sheet Metal Work
	B79-41T	3s ½H						. .	21	19.5	18		8	6	40	14	9	C	B	3s ½H	
	B79-41T	3s H						. .	29	27	25		4	4	55	16	10	G	B	3s H	
201	B109-41T	52s O				2.5	Cr 0.25	. .	29	(31 max.)	14		25	20	45	18	17	A	B	52s O	Strongest Work Hardening Alloy High Yield Strength and Fatigue Limit Highly Stressed Sheet Metal Products
	B109-41T	52s ½H						. .	37	34	29		10	7	67	21	19	D	B	52s ½H	
	B109-41T	52s H						. .	41	39	36		7	4	85	24	20.5	G	B	52s H	
									Precipitation Hardening Alloys(g)												
26	B78-41T	17s O	4		0.5	0.5		. .	26	(35 max.)	10		20	12	45	18	11	B	E	17s O	Duralumin. Most Common Strong Alloy Hardened by Quenching and Aging
	B78-41T	17s T						. .	60	55	37	32	20	18	100	38	15	H	D	17s T	
	B78-41T	17s RT						. .	65	55	47	42	13	12	110	38		J		17s RT	Available in Most Wrought Forms
		Alclad 17s T	(Coated with 99.75+Al)					. .	56	50	33	28	18	16		32		I	A	Alclad 17s T	Alclad Has Best Corrosion Resistance High Strength Heat Treated Forgings Best Forming Properties. Rivets
		17s T						Forging ½" Rod	55	50	30	30	16	16	100	36	15		D	17s T	
		A 17s	2.5			0.3			43		24		24		70	26	13.5	F	D	A 17s	
24		24s O	4.6		0.6	1.5		1/16" Sheet	26	(35 max.)	10		20	12	42	18	12	B	E	24s O	Strongest Alloy for Rolled Forms Used Widely in Aircraft Construction More Difficult to Form Than 17s High Strength Alclad; Corr. Resistance
		24s T						. .	68	62	44	40	19	17	105	41	18	J	D	24s T	
		24s RT						. .	70	65	55	50	13	12	116	42		K	D	24s RT	
		Alclad 24s T	(Coated with 99.75+Al)					. .	62	56	41	37	18	16		40		J	A	Alclad 24s T	
		61s W	0.25	0.55		1.0	Cr 0.25	. .	35		21		22		65	24	12.5	F	C	61s W	Good Forming Properties. High Yield Str Will Not Age Harden at Room Temp. Good Forming Properties and Corrosion Resistance
		61s T						. .	45		39		12		95	30	12.5	G	C	61s T	
		53s W		0.7		1.3	Cr 0.25	. .	33	28	20	16	22	17	65	20	10	F	B	53s W	
		53s T						. .	39	35	33	28	14	10	80	24	11	G	B	53s T	
280 27		A51s T		1.0		0.6	Cr 0.25	Forging	44		34		14		90	32	10.5		C	A51s T	For Intricate Forgings Good Forgeability. Lower Cost. Strongest Forging Alloy High Endurance Limit
		25s T	4.5	0.8	0.8			.	55		30		16		100	35	15		E	25s T	
		14s T	4.4	0.8	0.8	0.4		.	65		50		10		130	45	16		D	14s T	
		70s T	1.0		0.7	0.4	Zn 10	.	50		40		16		85	37	19		F	70s T	
		18s T	4			0.5	Ni 2	.	55		35		10		100	35			E	18s T	Strong at Elevated Temp.; Forged Pistons Forged Aircraft Pistons. "Low-X"
		32s T	0.8	12		1.0	Ni 0.8	.	52		40		5		115	38	14		C	32s T	
		11s T3	5.5			(Bi 0.5)	Pb 0.5	½" Rod	49		42		14		100	30	12.5		E	11s T3	Free-Cutting Screw Machine Products

Sand Casting Alloys

S.A.E.	A.S.T.M. B26-41T	Alcoa	Cu	Si	Fe	Mg	Zn	Condition	T.S.(b)		Y.S.(b)	Elongation		BHN	Shear	Endur.(c)	Impact	Corr.(e)	Alcoa	
33	CC	212	8	1.2	1			As Cast	22	19	14	2	0	50 to 70	20	7.5	0.6	D	212	General Casting Alloy. Not Heat Treated
38	C	112	7.5		1.2		1.5	. .	22	19	14	1.5	0	55 to 80	20	8	0.6	D	112	Good Casting Properties
31		645	2.8	1.2			11	. .	29	25	22	4	2.5	70	22.5	7.5	1	D	645	General Casting Alloy
35	JJ	43		5				. .	19	17	9	6	3	35 to 50	14	6.5	1	A	43	Thin, Pressure Tight Castings. Corr. Res.
37	K	47		12.5	(Trace Na)			Modified	26	24	11	8	5	45 to 60	18	6	3	A	47	Alpex or Silumin. High Strength, Elong.
38	G HT1	195 T4	4					Soln. H.T.	31	29	16	8	6	55 to 75	24	6	2.8	C	195 T4	High Strength Heat Treated Castings
38	G HT2	195 T6	4					H.T.	36	32	22	4	3	70 to 90	30	6.5	1.8		195 T6	Aircraft, Marine, Bus,
38	G HT3	195 T62	4					H.T.	40	36	31	2	0	80 to 100	31	7	1.3		195 T62	and Engine Parts
		A 334	3	4		0.3		As Cast	26	22	20	1.5	0	65	24		0.7	B	A 334	Intricate Castings
322-1	N HT1	355 T4	1.2	5		0.5		Soln. H.T.	30	26.5	20	5	3.5	50 to 65	28		1.3	A	355 T4	Liquid Cooled Cylinder Heads
322-2	N HT2	355 T6						H.T.	35	32	25	3.5	2	65 to 85	30		1.1		355 T6	Intricate Castings
322-3		355 T61						H.T.	38	35	33	1	0.5	80 to 95			0.8		355 T61	Good High Temperature Strength
	N HT3	355 T51						H.T.	28	25	23	1.5	0	50 to 70	22	6.5			355 T51	Water Jackets, Exhaust Manifolds
	M HT1	356 T4		7		0.3		Soln. H.T.	28	26	16	6	5	50 to 70	18		1.7	A	356 T4	Intricate Heat Treated Castings
	M HT2	356 T6						H.T.	32	30	22	4	3	60 to 80	22	8	1.0		356 T6	Good Corr. Resistance, Pressure Tightness
320	L	214				3.75		As Cast	25	22	12	9	6	40 to 60	19	5.5	3.8	A	214	" " " " Impact Toughness
324		220 T4				10		Soln. H.T.	44	42	25	14	12	70 to 85	33	7	4.5	A	220 T4	Highest Impact Toughness(h)
	F	122	10		1.2	0.2		As Cast		18.5			0					D	122	Common Piston Alloy. Wear Resistance
	F	122 T2						Soln. H.T.	25	23	21	1	0	75	25.5	9.5	0.7	D	122 T2	High Temperature Strength
	F	122 T61						H.T.	36	30	30	1	0	100	29.5		0.68	D	122 T61	Also Permanent Mold Castings
39	H	142	4			1.5	(Ni 2)	As Cast	28	23	24	1	0	85	24	8	0.6	C	142	High Temperature Strength and Stability
39	H	142 T61						H.T.	37	32	32	0.5	0	100	32	8		C	142 T61	Also Permanent Mold Castings

(a) Aluminum Co. of America Alloy No. & Heat Treatment Designations:
O = Annealed, W = As Quenched, T = Quenched & Aged, H = Cold Rolled to Hard Temper, ½H = Half Hard Temper, R = Cold Rolled After Heat Treatment, S = Wrought Alloy.

(b) In Thousands of Pounds per Square Inch. Yield Strength Taken at 0.2 % Permanent Set.

(c) 500 Million Cycles in Reverse Bending.

(d) Relative Forming Properties in Cold Bending; A = Best

(e) Relative Resistance to Salt Water Corrosion; A = Best

(f) Can Be Hardened by Cold Work Only.

(g) " " " " Heat Treatment.

(h) Special Foundry Practice Required.

Magnesium Alloys

Compositions, Properties, and Designations of American Commercial Alloys

Compiled by H. S. Jerabek, University of Minnesota, W. H. Gross of the Dow Chemical Co., and R. T. Wood of American Magnesium Corp.

Form	A.S.T.M. Alloy No.	A.S.T.M. Specification No.	Navy Bureau of Aeronautics Alloy No.	Navy Bureau of Aeronautics Specification No.	Navy Department Alloy No.	Navy Department Specification No.	U.S. Army Air Forces Grade	U.S. Army Air Forces Specification No.	S.A.E. No.	AMS(j)	Am. Mg. Corp. AM No.	Dow Chem. Co.	Composition, Per Cent Magnesium = Remainder Al	Mn	Zn	Condition	Tensile Strength (a) Typical	Tensile Strength (a) Min.	Yield Strength (a) Typical	Yield Strength (a) Min.	Elongation in 2 In., % Typical	Elongation in 2 In., % Min.	Brinell Hardness	Shear Strength (a)	Endurance (b)	Uses and Characteristics
Sand Castings	4	B80-41T	A	AN-QQ-M-56	A	AN-QQ-M-56	A	AN-QQ-M-56	50	4420A	265-C	H	6.0	0.2	3.0	As Cast	27	24	11	10	5	4	51	17	10	General casting use
							A			4422A	265-T4					Cast; Soln. T. (c)	37	30	12	10	10	7	53	18	10	Sand & permanent mold castings.
							A			4424A	265-T6					Cast; Soln. T.; Aged (d)	37	32	18	16	4	3	70	19	9	
	17	B80-41T	C	AN-QQ-M-56	C	AN-QQ-M-56	C	AN-QQ-M-56	500		260-C	C	9.0	0.1	2.0	As Cast	23	20	14	10	1		62	18	10	Pressure tight castings
											260-T4					Cast; Soln. T. (c)	39	32	14	10	10	6	61	20	10	Sand & permanent mold castings.
										4434	260-T6					Cast; Soln. T.; Aged (d)	38	34	20	18	3	1	77	22	10	
	2	B80-41T									240-C	G	10.0	0.1		As Cast	21	18	12	10	2	1	53	18	8	Sand & permanent mold castings.
											240-T4					Cast; Soln. T.; (c)	33	29	12	10	8	5	52	20	10	
											240-T61					Cast; Soln. T.; Aged (d)	34	29	19	17	1		69	22	8	
	3	B80-41T									246-T6	B	12.0	0.1		″ ″ ″	32	27	20	17	0.5		85	19	7	Hard castings. Pistons.
	11	B80-41T	B	AN-QQ-M-56	B	AN-QQ-M-56	B	AN-QQ-M-56			403-C	M		1.5		As Cast	14	12	4		5	3	33	11		Best salt water resistance.
											244-C		4.0	0.3		″ ″	24	20	9	8	6	4	44	14		Aircraft tank fittings.
Die Castings	12	B94-41T				46M11	1	11319			230-C	K	10.0	0.1	(f)	As Cast	30		22		1		68			Thin section die castings
	13	B94-41T				46M11	1	11319	501	4490	263-C	R	9.0	0.2	0.6	″ ″	33		20		3		66			General die castings.
Extruded Bars and Rods	8	B107-41T	8	M-314c(e)			1	11335(e)		4350A	57s	J	6.5	0.2	0.7	″ ″	43	40	30	26	17	12	54		17	Improved strength.
	8	B107-41T	8	M-314c(e)			1	11335(e)	520		57s	J	6.5	0.2	0.7	″ ″ ;Stretched(g)	44	40	32	26	15	12	55	20	15	Screw machine rod.
	11	B107-41T	11	M-314c			2	11336			3s	M		1.5		″ ″	42	32	27	20	6	3	42		10	Best salt water resistance
	9	B107-41T									58s	O	8.5	0.2	0.5	″ ″	47	43	33	28	11	9	61		17	Bars of high strength.
	15	B107-41T	15	M-314c(e)			1	11337(e)	521		C74s	X	3.0	0.2	3.0	″ ″	42	39	30	26	19	15	51		18	Heat treatable bar
	15a	B107-41T	15a	M-314c(e)			1	11337(e)	521		C74s-T5	X				″ ″ ;Aged	44	41	34	30	13	10	54		17	
											59s	G	10.0	0.1		″ ″ ;Stretched	51	45	38	33	9	6	70	23	16	Highest hardness & strength.
	18	B107-41T									52s	Fs	2.8	0.3	1.0	″ ″ ″	40	37	30	25	17	12	50	19	12	Good ductility & impact toughness.
Extruded Structural Shapes	8	B107-41T	8	M-314c(e)			1	11335(e)	520	4350A	57s	J	6.5	0.2	0.7	As Extruded	42	38	27	23	15	10	58			Good strength & weldability
	11	B107-41T	11	M-314c			2	11336			3s	M		1.5		″ ″	35	30	23	16	6	3	42			Best salt water resistance
	15	B107-41T	15	M-314c(e)			1	11337(e)	521		C74s-T5	X	3.0	0.2	3.0	″ ″	42	39	25	22	17	10	59			Heat treatable shapes.
	15a	B107-41T	15a	M-314c(e)			1	11337(e)	521		C74s	X				″ ″ ;Aged	43	40	28	25	14	8	62			
	9	B107-41T									58s	O	8.5	0.2	0.7	As Extruded	44	40	29	25	11	8	58			Improved strength
											59s	G	10.0	0.1		″ ″	48	45	37	30	9	6				Highest hardness & strength.
	18	B107-41T					1	11320(e)			52s	Fs	2.8	0.3	1.0	″ ″	39	34	28	17	15	10				Good ductility & impact toughness.
Extruded Tubing					8	44T35(e)	1	11332(e)	520		57s	J	6.5	0.2	0.7	As Extruded	40	36	19	17	9	7	55			Good strength & weldability
					11	44T35	2	11333			3s	M		1.5		″ ″	35	32	17	17	5	3	40			Best salt water resistance
					15	44T35(e)	1	11334(e)	521		C74s	X	3.0	0.2	3.0	″ ″	40	36	19	17	9	7	55			Heat treatable tubing
									521		C74s	X				″ ″ ;Aged	41	37	22	19	7	6	59			
											C58s-T5	O	8.5	0.2	0.7	″ ″ ″	42	39	29	25	5	4	60			Highest strength tubing.
							1	11318(e)			52s	Fs	2.8	0.3	1.0	As Extruded	35	32	16		11		50			Good ductility
Press Forgings	8	B91-41T			8	46M13(e)		11345		4350A	C57s	J	6.5	0.2	0.7	As Forged	41	38	25	22	9	6	56	21	17	General forging Good ductility
					11	46M13						M		1.5		″ ″	33	29	19	12	6	2	43			Weldable forgings.
	9	B91-41T			9	46M13(e)		11321A(e)		4360	C58s	O	8.5	0.2	0.5	″ ″	45	42	30	24	7	5	69	22	18	Forgings, simple design Strong
	15	B91-41T			15	46M13(e)					C74s	X	3.0	0.2	3.0	″ ″	41	38	24	20	16	9	59		17	Heat treatable forgings
	15a	B91-41T			15a	46M13(e)					C74s-T5	X				″ ″ ;Aged	42	38	28	22	14	7	62		17	
Hammer Forgings	16	B91-41T			16	46M13		11346			65s		3.5	0.2	(h)	As Hammer Forged	38	35	22	20	12	6	52	16	10.5	Hammer forgings.
												L	3.0	0.2	(i)	″ ″ ″	37	34	26	19	11	6	51		10.5	″ ″
Rolled Plate, Sheet & Strip	11	B90-41T			11	47M2	1	11339	51	4370	3s-H	Mh		1.5		As Hard Rolled	37	32	27	24	9	4	53			Sheet with best formability & salt water resistance.
									51	4370	3s-O	Ma				Annealed	32	28	16		15	12	44	17	8	
	8	B90-41T			8	47M2(e)	2	11338(e)		4381	C57S-H	J-1h	65	02	07	As Hard Rolled	45	40	35	28	8	3		20		Sheet with best combination of strength & salt water resistance
										4380	C57S-O	J-1a				Annealed	40	37	25		15	8		21		
	18	B90-41T			18	47M2(e)		11340(e)			C52S-H	Fs-1h	27	03	10	As Hard Rolled	45	38	35	26	9	4				General purpose sheet alloy.
											C52S-O	Fs-1a				Annealed	36	32	22		18	12				Good formability & strength.

(a) In 1000 psi. Yield strength is the stress at which the stress-strain curve deviates 0.2 % from the modulus line.

(b) Endurance or fatigue limit for 500 million reversals of the load, in 1000 psi.

(c) Solution heat treatment: Soaking at about 630 to 810 °F. followed by air quenching.

(d) Solution treatment followed by artificial aging at about 350 °F. (precipitation hardening).

(e) Compositions with 0.005 % Fe max. and 0.005 % Ni max., for improved resistance to salt water are required by these specifications. (Dowmetal J-1, O-1, X-1; AMC 57s, AM-C58s, AM-C74s, AM-C52S; ASTM 8x, 9x, 15x and 18x.

(f) Contains 0.5 % silicon.

(g) Extruded and stretched is the condition in which bar and rod is normally furnished.

(h) Contains 5.0 % tin.

(i) Contains 3.5 % cadmium.

(j) Aeronautical material specification, Society of Automotive Engineers, Inc.

Standard Brass and Bronze Alloys *of the Non-Ferrous Metal Institute*

Standard Ingot Alloy Number	Standard Ingot Alloy Designation	Chemical Specifications of Ingot Metal: Copper	Tin	Lead	Zinc	Iron	Aluminum (a)	Nickel	Incidental Elements (Max.): Mn	Sb	S	Si	P
Leaded tin bronze													
2A	88-6-1½-4½	87.0-89.0	5.75- 6.50	1.25- 1.75	3.50- 5.00	0.15 max.	None	0.75 max.	—	0.20	0.05	0.005	0.02
2B	87-10-1-2	86.5-88.5	9.25-10.5	0.75- 1.25	1.25- 2.50	0.15 max.	None	0.75 max.	—	0.25	0.05	0.005	0.03
High lead tin bronze													
3A	80-10-10	78.0-81.0 (b)	9.25-10.5 (b)	9.0 -11.0 (b)	0.75 max.	0.10 max.	None	0.50 max.	—	0.50	0.08	0.003	0.03
3B	83-7-7-3	82.0-84.0	6.50- 7.50	6.5 - 8.0	2.50- 4.00	0.20 max.	None	0.50 max.	—	0.20	0.08	0.003	0.02
3C	85-5-9-1	83.0-85.0	4.50- 5.50	8.5 -10.0	0.50- 1.50	0.15 max.	None	0.50 max.	—	0.25	0.08	0.003	0.02
3D	78-7-15	76.0-79.0 (b)	6.50- 7.50 (b)	14.0 -16.0 (b)	0.75 max.	0.10 max.	None	0.50 max.	—	0.75	0.08	0.003	0.03
3E	70-5-25	68.0-71.0 (b)	4.50- 5.50 (b)	23.5 -26.5 (b)	0.50 max.	0.10 max.	None	0.50 max.	—	0.75	0.08	0.003	0.03
Leaded red brass													
4A	85-5-5-5	84.0-85.5	4.50- 5.50	4.50- 5.50	4.50- 5.50	0.25 max.	None	0.50 max.	—	0.25	0.08	0.003	0.01
4B	83-4-6-7	82.0-83.5	3.50- 4.25	5.75- 6.75	6.00- 7.50	0.25 max.	None	0.50 max.	—	0.25	0.08	0.003	0.01
Leaded semi-red brass													
5A	81-3-7-9	79.5-81.5	2.75- 3.25	6.50- 7.50	8.50-10.0	0.35 max.	None	0.50 max.	—	0.20	0.08	0.003	0.01
5B	76-3-6-15	75.0-76.75	2.75- 3.25	5.50- 6.50	14.0 -16.0	0.35 max.	None	0.50 max.	—	0.20	0.07	0.005	0.01
Leaded yellow brass													
6A	71-1-3-25	70.0-71.75	0.75- 1.50	2.50- 3.50	25.0 (c)	0.50 max.	None	0.50 max.	—	0.10	0.05	0.05	0.01
6B	66-1-3-30	65.0-67.5	0.75- 1.25	2.75- 3.50	30.0 (c)	0.50 max.	None	0.50 max.	—	0.10	0.05	0.05	0.01
6C	60-1-1-38	58.0-61.0	0.75- 1.25	0.75- 1.25	37.85 (c)	0.50 max.	0.10- 0.20	0.50 max.	—	0.10	0.05	0.05	0.01
Leaded high strength yellow brass (manganese bronze)													
7A	60,000-20 (d)	56.0-60.0	0.50- 1.00	0.50- 1.00	37.5 (c)	0.75-1.50	0.25- 1.00	0.50 max.	0.50 (g)	0.05	0.05	0.10	0.005
High strength yellow brass (manganese bronze)													
8A	70,000-30 (e)	56.0-59.0	0.50 max.	0.25 max.	39.25 (c)	0.75-1.50	0.75- 1.50	0.50 max.	0.50 (g)	0.01	0.05	0.03	0.005
8B	100,000-10 (f)	61.0-63.5	0.05 max.	0.10 max.	26.50 (c)	2.50-3.50	4.50- 6.00	1.00 max.	4.50 (h)	0.01	0.03	0.10	0.005
Aluminum bronze													
9A	87½-3½-9	86.5-88.0 (i)	0.10 max.	0.05 max.	0.10 max.	3.25-3.75 (i)	8.50- 9.50 (i)	0.25 max.	0.25	0.01	0.05	0.10	0.005
9B	89-1-10	88.25-89.5 (i)	0.10 max.	0.05 max.	0.10 max.	0.75-1.25 (i)	9.75-10.5 (i)	0.25 max.	0.25	0.01	0.05	0.10	0.005
Leaded nickel brass (nickel silver)													
10A	57-2-9-20-12	55.0-58.0	1.50- 2.50	8.00-10.0	20.0 (c)	1.00 max.	None	11.0-13.0	0.50	0.25	0.05	0.01	0.05
10B	60-3-5-16-16	58.0-61.0	2.50- 3.50	4.50- 5.50	16.0 (c)	1.00 max.	None	15.5-17.0	0.50	0.25	0.05	0.03	0.05
Leaded nickel bronze (nickel silver)													
11A	64-4-4-8-20	63.0-65.0	3.50- 4.50	3.50- 5.00	7.00-10.0	(j)	None	19.5-21.0	1.00	0.25	0.05	0.05	0.05
11B	66-5-1½-2-25	64.0-67.0	4.00- 5.50	1.00- 2.00	1.00- 3.00	1.00 max.	None	24.0-26.0	1.00	0.25	0.05	0.10	0.05

Index of Corresponding or Similar Specifications

Specifications for Ingots: Non-Ferrous Ingot Metal Institute	A.S.T.M. B30-40T	Federal Specifications Board (k)	U.S. Navy	Specifications for Castings from Given Ingot: Federal Specifications Board and U.S. Army	U.S. Navy	U.S. Air Corps	S.A.E., A.M.S. (l)	Society of Automotive Engineers
Leaded tin bronze								
2A	2A	QQ-B-701 (No. 1)	F.S.B. (m)	QQ-B-691a (No. 1)	F.S.B. and 46B8g	F.S.B. (m)		—
2B	2B	QQ-B-701 (No. 6)	F.S.B.	QQ-B-691a (No. 6 and 6X)	F.S.B.	F.S.B.	4845 A (n)	No. 63
High lead tin bronze								
3A	3A	—	—	—	—	—	4842	No. 64
3B	3B	—	—	—	—	—		No. 660
3C	3C	—	—	—	—	—		No. 66
3D	3D	QQ-B-701 (No. 7)	F.S.B.	QQ-B-691a (No. 7)	F.S.B. and 46B22d (No. 1)	F.S.B.		No. 67
3E	3E	—	—	—	46B22d (No. 5)	—	4840	—
Leaded red brass								
4A	4A	QQ-B-701 (No. 2)	F.S.B.	QQ-B-691a (No. 2)	F.S.B. and 46B23c	F.S.B. and 11306 Grade A		No. 40
4B	4B	—	—	—	—	—		—
Leaded semi-red brass								
5A	5A	QQ-B-701 (No. 4)	F.S.B.	QQ-B-691a (No. 4)	F.S.B. and 46B24c	F.S.B.		—
5B	5B	—	—	—	—	—		—
Leaded yellow brass								
6A	6A	—	—	—	—	—		—
6B	6B	—	—	QQ-B-621 (Grade B)	F.S.B. and 46B11c	F.S.B.		No. 41
6C	6C	—	—	QQ-B-621 "A"	F.S.B. and 46B10f	F.S.B.		—
Leaded high strength yellow brass (manganese bronze)								
7A	7A	—	—	—	—	—		—
High strength yellow brass (manganese bronze)								
8A	8A	QQ-B-731a	F.S.B. and 46B16b	QQ-B-726a	F.S.B. and 49B3c	F.S.B.	4860	No. 43
8B	8B	—	—	—	46B29 (A and B)	—	4862 (o)	—
Aluminum bronze								
9A	9A	—	46B19a	QQ-B-671 Grade A	F.S.B. and 46B18c	F.S.B.	4871	No. 68 (Grade A)
9B	9B	—	—	QQ-B-671 Grade B	F.S.B.	F.S.B. and No. 11076		No. 68 (Grade B)
Leaded nickel brass (nickel silver)								
10A	10A	—	—	—	—	—		—
10B	10B	—	—	—	—	—		—
Leaded nickel bronze (nickel silver)								
11A	11A	—	—	(p)	—	—	—	—
11B	11B	—	—	—	—	—	—	—

Notes

(a) "None" is defined as 0.005% when determined on 10-g. sample.

(b) Copper plus tin plus lead must total 98.50%.

(c) Nominal (remainder).

(d) Minimum tensile strength 60,000 psi.; minimum elongation in 2 in., 20%.

(e) Minimum tensile strength 70,000 psi.; minimum elongation in 2 in., 30%.

(f) Minimum tensile strength 100,000 psi.; minimum elongation in 2 in., 10%.

(g) 0.10% min.

(h) 3.00% min.

(i) Copper plus iron plus aluminum must total 99.50%.

(j) Nominally 1.00% max., but total impurities including iron but excluding manganese must be 1.00 max.

(k) U.S. Army and Air Corps use Federal Specifications Board (Federal Standard Stock Catalog) for ingots.

(l) Society of Automotive Engineers, Aeronautical Material Specifications.

(m) When marked F.S.B. the service uses the Federal Specifications Board (Federal Standard Stock Catalog).

(n) Lead is limited to 0.20% max.

(o) Copper 63% min.; tensile strength 115,000 psi. min.; elongation in 2 in., 12% min.

(p) FF-H-106
FF-H-111
FF-H-116a
FF-H-121a
FF-H-136
WW-P-541

Aluminum Bronzes Commonly Used in Aircraft

Compiled by W. W. Edens, Ampco Metal Inc.

Nominal Composition	Form or Condition	Specification Met (2)	Tensile Strength, Psi	Yield Strength, (0.5% Elon), Psi	Proportional Limit, Psi (Min)	Elon in 2 In., %	Reduction of Area, %	Brinell Hardness, (3000 kg)	Rockwell Hardness	Elastic Limit in Compression, Psi	Impact (Min) Izod, Ft-Lb.	Impact (Min) Charpy, Ft-Lb.	Metallographic Structure	Representative Uses in Aircraft
90% Cu 9% Al 1% Fe	Rods, Bars, Forgings	AMS-4630 A	72-80,000	33-40,000	20,000	15-25	15-25	130-170	72-83B	30,000			Primary α, Small Am't & Eutectic	Motor Parts, Bearing Liners, Thrust Pads, Retainer Plates, Bushings, Guides, Gears
	Rods, Bars	AMS-4632	72-80,000	40-50,000	25,000	5-15	5-15	175-200	88-94B	40,000			Primary α, Many Twinned Crystals Due to Cold Work	Misc Guides, Gears, Bushings
	Cast and Heat Treated	QQB-671a Class B	80-88,000	40-45,000	22,000	12-20	12-20	140-163	84-92B	35,000	25	17	Primary and Reprecipated α in Beta Matrix	Gun Mountings, Trunnion Yokes, Gears, Bushings, Landing Gear Nuts
	*													
88.6% Cu 8.6% Al 2.8% Fe	Sand Cast	QQB-671a "A" 46B-18c SAE-68	65-75,000	28-34,000	14,000	22-30	22-30	116-130	65-72B	18,000	75	60	Primary Alpha	Misc Bushings, Bearings, Slides & Mountings
	Centrifugal Cast	QQB-671a "A" 46B-18c SAE-68	75-85,000	29-35,000	15,000	28-36	28-36	120-140	66-73B	18,500	75	60	Primary α in Small Am't of Beta Matrix	Same as Sand Cast But Preferred Where Type of Casting Permits
	*													
87.0% Cu 9.8% Al 3.2% Fe	Bars, Rods, Forgings (1)	QQB-666 "B" 46B-17	72-95,000	35-55,000		15-25	15-25	140-200	84-94B	40,000			Primary α With Beta & Eut. Matrix	Landing Gear Bushings, Nuts and Other Parts. Windshield and Defroster Parts
	Centrifugal Cast	QQB-666 "B" 46B-17 (On Approval)	80-90,000	30-40,000	15,000	20-27	20-27	131-159	73-83B	25,000	40	30	Primary α in Beta & Eutectic Matrix	Substituted for Wrought Material in Larger Sized Work Where Bushing Stock Conserves Time & Waste of Material
	*													
85.6% Cu 10.8% Al 3.6% Fe	Sand Cast	QQB-671a "C"	77-85,000	35-42,000	18,000	12-20	12-20	159-183	83-90B	30,000	25	17	Primary α in Beta & Eutectic Matrix	Wear Plates, Hinge Plates, Pump Bodies, Gears, Bushings
	Centrifugal Cast	QQB-671a "C" PWA-241	90-100,000	38-45,000	19,000	6-12	6-12	179-207	88-94B	32,000	28	19	Primary α in Beta & Eutectic Matrix	Propeller Blade Bushings, Pump Parts, Bearings, Bushings, Gears
	Cast and Heat Treated	QQB-671a "D"	90-100,000	45-50,000	30,000	10-15	10-15	179-207	88-94B	45,000	20	14	Reprecipated α in Beta Matrix	Propeller Parts, Propeller Hub Nuts, Landing Gear Parts, Misc Bushings & Bearings
	Cast and Heat Treated	AN-QQB-672 (Air Corps 11076)	85-95,000	47-54,000	33,000	3-7	3-7	202-235	93-99B	50,000	18	11	Reprecipated α in Beta Matrix	Propeller Rear Cones, Landing Gear Parts, Valve Seats, Tail Wheel Parts
	*													
81.2% Cu 10.8% Al 4.0% Ni 4.0% Fe	Rods, Bars Heat Treated	AMS-4640	90-100,000	45-50,000	35,000	5-10	5-10	202-235	93-99B	50,000	18	11	Alpha in Beta & Eutectic Matrix	Misc. Bushings & Bearings, Guides, Valve Seats
	Cast and Heat Treated	AN-QQB-672 (Air Corps 11076)	90-100,000	45-50,000	33,000	5-10	5-10	202-235	93-99B	50,000	18	11	Reprecipated & Some Primary α in Beta Matrix	Landing Gear Parts, Propeller Locking Nuts, Valve Seats
	*													
81.3% Cu 14.0% Al 4.7% Fe	Centrifugal Cast	HSP-22	80-90,000	45,000 Min		1-3	1-3	311-350	34-38C	65,000	9	4	Delta Crystals in Beta & Eut Matrix	Propeller Cam Rollers, Drawing & Forming Dies for Carbon & Stainless Steels & Aluminum
	*													

(1) Properties Very With Diameter & Anneal.

(2) Ranges of Properties Are Commercial Ranges Available Although in Many Cases Low Figure of Range is Specification Minimum.

* Spaces Left Open for Chart Users to Add Specialized Alloys of Similar Composition with Properties Varied by Heat Treatment or Cold Work to Meet Unusual Application.

Note—Modulus of Elasticity is Approx 15,000,000 for All Alloys. Weight per Cubic Inch is Approx 0.27 Lb for All Alloys. Coefficient of Expansion is 0.000009 In. per In per °F. for All Alloys.

Properties of Important Wrought Chromium-Nickel-Iron Alloys

Revised 1943, from data furnished by U.S. Steel Corp., Electro Metallurgical Co., and Commitee A-10, A.S.T.M.

Nominal Alloy A.I.S.I. Type No.	18-8 302†	18-8 Ti 321	18-8 Cb 347	18-12 Mo 316	20-12 308	24-12 309	25-20 310	18-26 311
Chemical composition								
Chromium	17 to 19	17 to 19	17 to 19	16 to 18	19-22	22 to 24	24 to 26	18 to 20
Nickel	8 to 10††	8 to 11	9 to 12	10 to 14	10-12	12 to 15	19 to 22	24 to 26
Mn (max.)	1.25	2.00	2.00	2.50	2.00	2.00	2.00 max.	2.00 max.
Carbon	0.08 to 0.20	0.10 max	0.10 max.	0.10 max	0.10 (max)	0.20 max	0.25 max	0.25 max.
Others	—	Ti 4 x C	Cb 10 x C	2 to 3 Mo	—	—	—	—
Specific gravity								
Lb. per cu. in.	0.288	0.286	0.29	0.291	0.287	0.29	0.285	0.280
(Mild steel = 1.00)	1.02	1.01	1.02	1.03	1.01	1.01	1.01	0.99
Electrical resistance at 70°F.								
Microhm per cm³	72*	72	73	74	—	78	80±	102
(Mild steel = 1.00)	6.6	6.6	6.7	6.8	—	7.1	7.3	9.3
Melting range, °F.								
Top	2590	2600		2550	2590	2650	2650	—
Bottom	2550	2550		2500	2550	2550	2550	—
Structure	Austenitic	Austenitic		Austenitic	Austenitic	Austenitic	Austenitic	
Magnetism								
Ferromagnetic	—	—	—	—	—	—	Trace	—
Permeability As annealed	1.003	1.003	1.02	1.003	—	1.003	1.003	—
Permeability Cold Worked	1.10 to 7.0	—	—	1.10 to 10.0	—	—	—	—
Specific heat								
Cgs units, 0 to 100°C.	0.12	0.12		0.12	—	0.12	0.14	—
(Mild steel = 1.00)	1.1	1.1		1.1	—	1.1	1.3	—
Thermal conductivity								
** Cgs units at 100°C.	0.0388	0.0385		0.0372	0.039	0.03 to 0.04	0.0330	—
(Mild steel = 1.00)	0.33	0.32		0.316	0.33	0.25 to 0.35	0.280	—
Cgs units at 500°C.	0.0512	0.0528		0.0499	—	—	0.0413	—
Thermal expansion per °F. x 1,000,000								
From 32 to 212°F.	9.5	9.3		8.9	9.6	8.3	8.0	8.8
(Mild steel = 1.00)	1.44	1.40		1.35	1.45	1.26	1.21	1.33
From 32 to 932°F.	10.2	10.2		9.7	—	9.6	9.2	9.3

Mechanical Properties at Room Temperature	18-8 Annealed	18-8 Cold Worked (Type 301X)†	321, 347 Annealed	316 Annealed	316 Cold Worked	308 Annealed	309 Annealed	309 Cold Worked	310 Annealed	311 Annealed
Tensile strength, 1000 psi.	80 to 100	150 to 300	75 to 95	80 to 95	140 to 200	70 to 90	90 to 100	110 to 270	80 to 110	90 to 110
Yield strength, 1000 psi.	30 to 45	130 to 275	30 to 45	35	120 to 180	30 to 60	40	65 to 230	35 to 55	45 to 50
Elastic modulus, 10^6 psi.	28	26 to 28	29	28	—	28	29	—	30	30±
Elongation, % in 2 in.	65 to 45	20 to 2	60 to 45	65 to 50	18 to 6	75 to 50	55 to 35	15 to 3	60 to 45	35 to 30
Reduction of area, %	70 to 50	55 to 10	65 to 50	70 to 55	65	70 to 45	60 to 50	55 to 20	60 to 50	45 to 35
Impact, ft-lb.; Charpy	90 to 60	—	80	80	—	—	90 to 60	—	80 to 70	—
Izod	110 to 75	50 to 20	100	100	—	—	—	—	100 to 60	50 to 90
Fatigue endurance limit, 1000 psi.	30 to 40	85	45	39	—	—	42	—	—	—
Hardness, Brinell	150 to 160	365 to 410	135 to 149	135 to 165	—	135 to 185	150 to 185	170 to 325	160	160 to 185
Rockwell	B-75 to 80	C-36 to 50	B-75	B-75 to 90	C-30 to 38	—	B 80 to 90	C-5 to 40	B-80	—
Erichsen value, mm.	10 to 14	—	12	12	—	—	7 to 8	—	—	—
Stress in psi. causing 1% "creep" in 10,000 hr at 1000°F	17,000		321: 18,000 347: 19,000	23,000			17,000		17,000	17,000*
1200	7,000		321: 7,800 347: 9,500	10,000			8,500		9,000	—
1350	2,500		321: 3,600 347: 4,000	5,500			3,500		3,300	—
1500	850		321: 850 347: —	2,000			1,000		1,100	—
1600	—		321: — 347: —	—			—		—	1,900
Scaling temp., °F.	1650		1650	1650		1650	2000		2000	1650
Initial forging temp., °F.	2000 to 2200		2100 to 2200	2100 to 2200		—	2000 to 2150		2000 to 2150	2050
Finishing temp., °F.	Not under 1700		Same as 18-8	As for 18-8		—	Not under 1800		1800 to 1850	1700
Annealing treatment	Heat at 1950 to 2050°F and Quench		Same as 18-8	1950 to 2050 °F and Quench		—	Heat at 2000 to 2100°F. and Quench		Same as for 24-12	2000° (Quick Heat & Quench)

* Electrical resistance of cold worked 18-8 ranges from 70 to 82 microhms per cm cube

** Thermal conductivity is measured as calories per sq. cm per sec per °C per cm.

† Type 301X is the cold-worked sheet for light weight structure

†† For spinning purposes Ni is sometimes specified 10 to 12%

The A-B-C of Corrosion & Heat Resisting Steels

Arrangement due to F. R. Palmer. Adapted from The Book of Stainless Steels, Second Edition

Group A (Martensitic)	Group B (Ferritic)	Group C (Austenitic)
Chemical Analysis Chromium less than about 16%; carbon in balance but ordinarily less than about 0.40%. May contain a little tungsten, nickel, silicon, columbium, aluminum, and more frequently molybdenum. Magnetic.	Chromium more than about 16%; carbon quite low, but can increase as chromium goes up. May contain small percentages of copper, nickel, silicon, molybdenum, tungsten, nitrogen. This group is magnetic.	Contains enough nickel to make steel austenitic and non-magnetic. They usually contain twice as much chromium as nickel or vice versa; total alloy content at least 24%. Carbon quite low. (Manganese sometimes substituted for nickel, in part.)
Heat Treatment Respond to hardening and tempering. Resulting physical properties depend on chemical analysis (principally carbon content).	Harden hardly at all. 18% Cr toughened by long anneal at more than 1400° F., and air cooling. Avoid decarburizing the skin. 25% chromium gets best strength and toughness by rapid cooling from 1650°.	Do not respond to hardening by heat treatment. Must be rapidly cooled from soaking heat at 1900 to 2150° F. to retain austenitic structure free of carbides. (Brinell 140 to 170).
Toughness Are structurally dependable after heat treatment; not brittle in notched sections or under impact. Suffer some loss in impact after tempering in 800 to 1100° F. range.	Laminated structure, from coarse ferrite in ingot, causes low impact values, but proper rolling and heating gives adequate toughness in rods, bars, and sheets. Structure is refined by alloying with nitrogen.	Extremely tough at all temperatures down to liquid air. Dependable against shock except when corroded at grain boundaries (a preventable condition).
Grain Growth and Structural Changes at High Temperatures Not subject to excessive grain growth. Thoroughly dependable for supporting any load or shock within their carrying capacity up to 1400° F. Brittleness in plain chromium steels when cooled after long heating is avoided by addition of molybdenum.	The chromium-irons low in carbon and those high in silicon or aluminum (when cold worked) are subject to excessive grain growth, especially above 1900° F. Grain growth reduced by nitrogen. Long service at temperatures up to 1600° F. makes them brittle when cold, although they are not brittle at working temperatures.	Alloys near the austenite-martensite border line tend to precipitate carbides at grain boundaries during service at 800 to 1600° F., losing some toughness and becoming susceptible to intergranular attack. This is controlled by very low carbon, by titanium or columbium, by increasing the chromium and nickel, or by prior "stabilization."
Strength at Elevated Temperatures Much better than straight carbon steel for temperatures up to 1000 or 1200° F. Retain tensile properties up to 750° F.	Heat resisting varieties quite tough at temperatures up to 1600° F. Inferior to Group C in creep resistance.	Have high creep strength up to 1200° F. which is enhanced by tungsten or molybdenum. Toughness impaired in non-stabilized alloys by service at 800 to 1600° F.
Hot Working Qualities Readily forged, pierced, or rolled at 2000 to 1700° F. Preheat and soak stock at 1600° F. Plain high chromium steels air harden on cooling.	May be forged, rolled, or pierced. Should be heated quickly. Forge from 2200° F. down to 1750° F. On last heat continue gingerly down to 1400° to refine grain; then anneal. Alloys do not air harden.	May be forged, rolled, or pierced. Preheat and soak at 1600° F., heat quickly to 2200° F., forge down to 1850° F. Hot short range: 1800 to 1300° F. Alloys do not air harden.
Cold Working Qualities Low carbon varieties can be easily cold drawn into wire, cold rolled, bent, formed, upset, coined, and deep drawn.	Can be cold drawn into wire, cold rolled, bent, formed, upset, coined, and deep drawn, especially when warm (300 to 500° F.).	Can be cold drawn into wire, cold rolled, bent, formed, upset, coined, and deep drawn. Work-harden twice as rapidly as Groups A and B.
Machinability Machine satisfactorily with properly designed tools when heat treated to 200 to 250 Brinell. Free-cutting grade contains complex sulphides or selenium.	Machine satisfactorily with properly designed tools. Cold working and high sulphur or selenium improve machinability.	Most difficult of all even with super high speed and carbon tools. Use sharp tools having greater top rake than usual, and cut continually. Free-cutting grade contains sulphur or selenium and phosphorus.
Riveting Make excellent cold rivets. Air hardening, high chromium steels not recommended for hot rivets driven above 1500° F.	Extra precautions required to avoid brittle rivets. Conical heads should be cold upset on ground bars; rivets driven at 1425° F. into chamfered holes.	Excellent for either hot or cold rivets. Hot rivets may be driven at a high temperature (1900° F.).
Welding Properties Preheated parts can be welded with gas, electric arc, or resistance. Anneal immediately before weld air hardens. Little grain growth. Columbium or aluminum increases ductility of welds.	Can be welded. Anneal to reduce embrittlement alongside weld. Those metals subject to grain growth are brittle adjacent to the weld. Those metals not subject to grain growth yield satisfactory welds.	Can be welded with gas, electric arc, or resistance. Weld does not air harden and is very tough. Only the very low carbon or alloys stabilized with Ti, Co or Mo should be welded if article must resist corroding media.
Corrosion Resistance Increases with chromium content; inferior to Groups B and C. Resists weather, water, steam, and mild corrodents when chromium is 11.5% or more. If carbon is relatively high, metal must be hardened and tempered (below 1000° F.).	Possess corrosion resisting properties superior to Group A; increases with chromium content. Especially good for nitric and other oxidizing acids.	Corrosion resistance depends largely upon total alloy content. Markedly improved by molybdenum. Resists nearly all corrodents measurably better than Groups A and B; especially good for organic acids. Severe pitting may occur in stagnant chloride solutions.
Scale Resistance Increases with chromium content. Generally useful for continuous temperatures up to 1200° F., and in some services up to 1500° F.	Superior to Group A, especially when chromium is above 25%; then resist reducing atmospheres up to 2100° F., resist oxidizing gases up to melting points, and sulphur gases up to 1800° F.	Excellent where combination of high temperature and corrosion is to be met. High chromium, low nickel alloys required to resist sulphurous gases. Addition of 2 to 3% silicon markedly improves scale resistance.

Properties of Important Wrought Chromium-Iron Alloys

Revised 1943, from data furnished by U.S. Steel Corp., Electro Metallurgical Co., and Commitee A-10, A.S.T.M.

Nominal Alloy A.I.S.I. Type No.	2% Cr —	5% Cr 502		9% Cr —	12% Cr 410;416		Cutlery 420		17% Cr 430		27% Cr 446	
Chemical composition												
Chromium	1.75 to 2.25	4 to 6		8 to 10	10 to 14		12 to 14		16 to 18		23 to 27	
Molybdenum	0.6	0.5		1.0 or 1.5	(0.6 max.)		—		(0.5 max. Ni)		(1.0 max Ni)	
Mn (max.)	0.65	0.50		0.5	0.5		0.55		0.5		1.5	
Carbon	0.15 max.	0.10 to 0.20		0.15 max.	0.15 max.		0.30 to 0.40		0.12 max.		0.35 max.	
Specific gravity												
Lb. per cu. in.	—	0.28		0.282	0.28		0.278		0.277		0.273	
(Mild steel = 1.00)	—	0.99		1.00	0.98		0.98		0.98		0.96	
Resistance at 70 °F.												
Microhms per cm³	—	35		—	57		60		60		67	
(Mild steel = 1.00)	—	3.2		—	5.2		5.5		5.5		6.1	
Melting range, °F.												
Top	—	2800		—	2790		2750		2750		2750	
Bottom	—	2700		—	2700		2580		2700		2700	
Structure (normal)	Pearlitic	Martensitic		Martensitic	Martensitic or Ferritic		Martensitic		Ferritic		Ferritic	
Magnetism												
Ferromagnetic	Yes	Yes		Yes	Yes		Yes		Yes		Yes	
Permeability: As annealed	—	—		—	—		—		—		—	
Permeability: Cold worked 10%	—	—		—	—		—		—		—	
Specific heat												
C.g.s. units, 0 to 100 °C.	0.11	0.11		0.11	0.11		0.117		0.11		0.12	
(Mild steel = 1.00)	1.0	1.0		1.0	1.0		1.1		1.0		1.1	
Thermal conductivity												
* C.g.s. units at 100 °C.	—	0.0874		—	0.0595		0.054		0.0595		0.0500	
(Mild steel = 1.00)	—	0.73		—	0.50		0.45		0.50		0.42	
C.g.s. units at 500 °C.	—	0.0804		—	0.0686		—		0.0624		0.0581	
Thermal expansion per °F. x 1,000,000												
From 32 to 212 °F.	—	6.2		6.2	6.1		5.7		5.6		5.9	
(Mild steel = 1.00)	—	0.94		0.94	0.93		0.87		0.86		0.90	
From 32 to 932 °F.	7.3	7.2		6.9	6.7		6.6		6.7		6.3	
Mechanical Properties at Room Temperature	Annealed	Annealed	Quenched (1600°); Tempered (1000°)	Annealed	Annealed	Quenched & Tempered (800-1300°)	Annealed	†† Heat Treated	Annealed	Cold Worked (Wire)	Annealed	Cold Worked (Wire)
Tensile strength, 1000 psi.	60 to 70	65 to 85	175	70 to 87	65 to 85	90 to 180	90	230 to 260	70 to 80	90 to 110	75 to 95	85 to 175
Yield strength, 1000 psi.	30 to 45	30 to 60	145	35 to 45	35 to 45	70 to 160	65	200 to 220	40 to 50	80	50 to 60	55 to 155
Elastic modulus, 10^6 psi.	29	29	—	29	29	29	29	—	29	—	29	—
Elongation, % in 2 in.	40 to 30	45 to 35	17	40 to 25	35 to 25	25 to 15	27	5	30 to 25	25 to 8	30 to 20	25 to 2
Reduction of Area, %	65 to 45	75 to 60	60	70 to 50	65	65 to 45	59	7	75 to 50	70	60 to 50	55 to 25
Impact, ft-lb., Charpy	35 to 65	45 to 75	—	45	—	—	—	—	—	—	—	—
Izod	—	75 to 85	32	90	100 to 60	20 to 30	65	—	—	—	2	—
Fatigue endurance limit, 1000 psi.	—	—	—	—	43	55	50	—	34	50	50	—
Hardness, Brinell	130 to 160	135 to 180	300	145 to 180	135 to 165	180 to 380	190	480	175	197	160 to 190	150 to 250
Rockwell	—	B-75 to 85	C-24	—	B-80	—	B-90	C-54	B-80	B-97	B-85	C-0 to 25
Erichsen value, mm.	—	—	—	—	7 to 8	—	—	—	7 to 9	—	—	—
Olsen value, In.	—	0.375 to 0.450	—	—	—	—	—	—	—	—	—	—
Stress in psi. causing 1% "creep" in 10,000 hr. at 1000 °F.	11,000	9,000		11,000	12,000		4,500		8,500		6,200	
1100	5,500	4,500		6,950	4,700		1,700		5,000		3,000	
1200	3,000	2,100		2,400	2,200		1,300		2,100		1,600	
1350	—	—		—	1,400				1,000		400	
Scaling temp., °F.	1100	1,150		1200	1,250		1,250		1,550		2,000	
Initial forging temp., °F.	2200	2,100 to 2200		2,000 to 2,150	2,000 to 2,100		2,000 to 2,100		1,900 to 2,050		1,900 to 2,000	
Finishing temp., °F.	1500	1,500 to 1,600		1600	1,500		1,700 to 1,750		1,500		1,300 to 1,450	
Annealing treatment	†	†††		***	**		Cool from 1,450 to 1550		Air cool from 1,400 to 1,450		Rapid cool from 1,450 to 1,550	

* Thermal conductivity is measured as calories per sq.cm. per sec. per °C. per cm.
†† Oil quenched from 1850 °F. and tempered
** Furnace cool from 1550 to 1100 °F., or air cool from long heat at 1250 to 1350 °F.
*** Cool from 1325 to 1375 °F. or slow cool from 1600 to 1675 °F.
††† " " " " " " " " " 1525 to 1600 °F.
† Furnace cool from 1620 °F.

Engineering Properties of Monel

Data from
International Nickel Co., Inc.

Monel is a solid solution of nickel and copper approximately 67:30, with added elements to control certain properties. Typical compositions are as shown at right:

Product	Ni	Cu	Fe	Mn	Si	C	Al	S
Wrought: Regular	67	30	1.4	1.0	0.1	0.15	....	(Note)
"K" (heat treatable)	66	29	0.9	0.4	0.50	0.15	2.75	0.005
Cast; Regular	67	29	1.5	0.9	1.25	0.3	...	.....
"H" (high strength)	65	29.5	1.5	0.9	3.0	0.1	....	.....
"S" (non-galling)	63	30	2.0	0.9	4.0	0.1	....	.....

(Note) A high sulphur variety called "R" Monel is free machining.

Properties of Monel Castings

Property	Regular	H Monel	S Monel
Tensile strength (1000 psi.)	65 to 90	90 to 115	110 to 145
Yield (1000 psi. for 0.5% extension)	32.5 to 40	45 to 75	80 to 115
Elongation (% in 2 in.)	45 to 25	20 to 10	4 to 1
Izod impact, ft-lb.	80 to 65	45 to 35	5 to 1
Brinell hardness	125 to 150	175 to 250	275 to 375
Rockwell number	55 to 75-B	......	<32-C

Temperature for slight oxidation	570° F.
Annealing range (standard monel)	1400 to 1800° F.
Forging range (standard monel)	2150 to 1600° F.
Pouring range for castings	2700 to 2850° F.

Cold-Rolled Sheet and Strip

Temper	Sheet		Strip		Approx. Tensile Strength
	Shore	Rockwell B	Shore	Rockwell B	
Dead soft	16 max.	60 max.	16 max.	60 max.	70,000
Soft	......	......	17 to 18	61 to 68	75,000
Soft skin-hard	17 to 20	61 to 73	......	......	......
Skin hard	......	......	19 to 20	69 to 73	77,500
Quarter hard	21 to 24	74 to 82	21 to 24	74 to 82	80,000
Half hard	25 to 30	83 to 89	25 to 30	83 to 89	90,000
Three quarter	31 to 35	90 to 93	31 to 35	90 to 93	100,000
Hard	36 min.	94 min.	36 to 40	94 to 97	110,000
Full hard (strip)	......	......	41 min.	98 min.	120,000

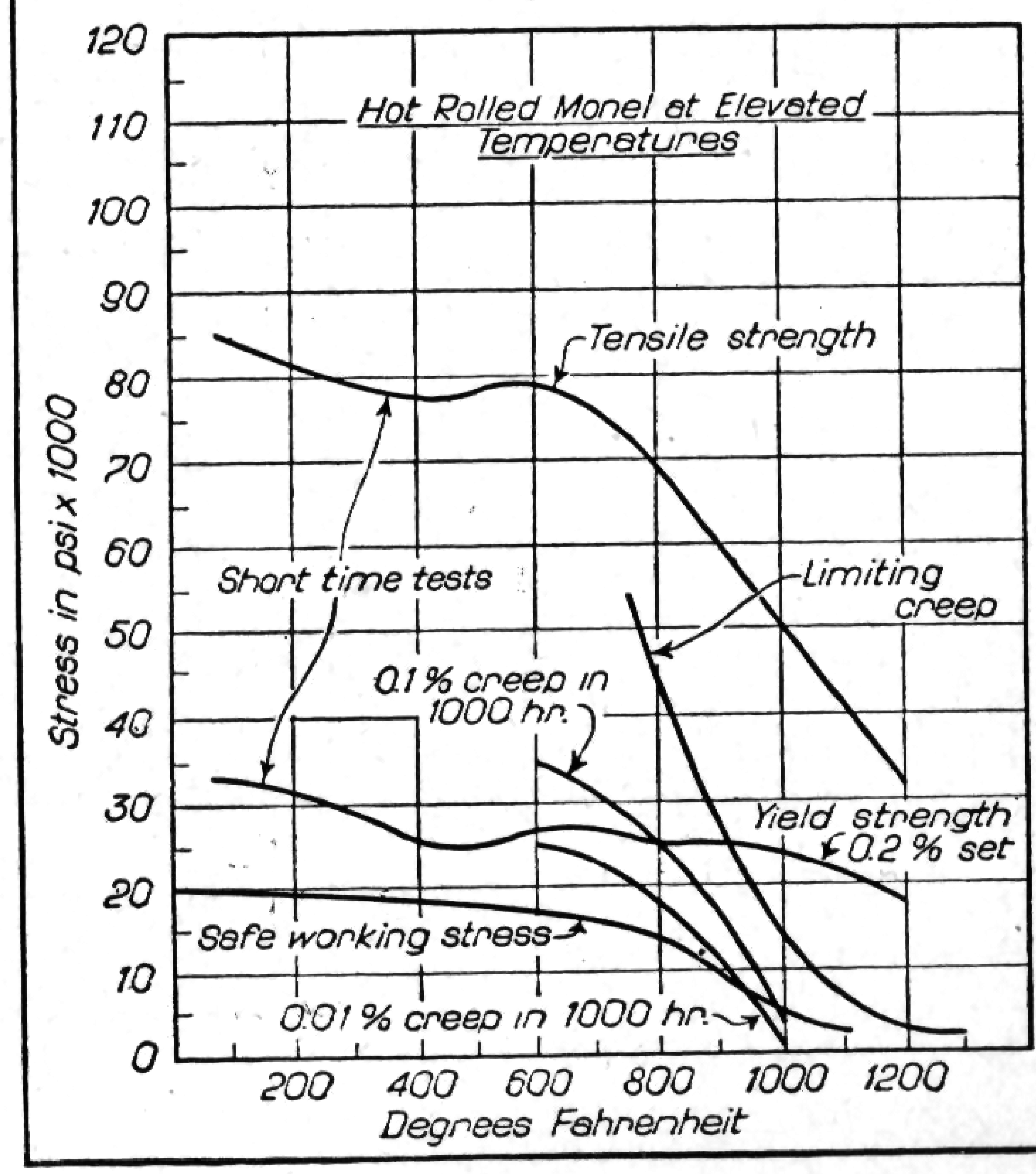
Physical Constants of Wrought Monel

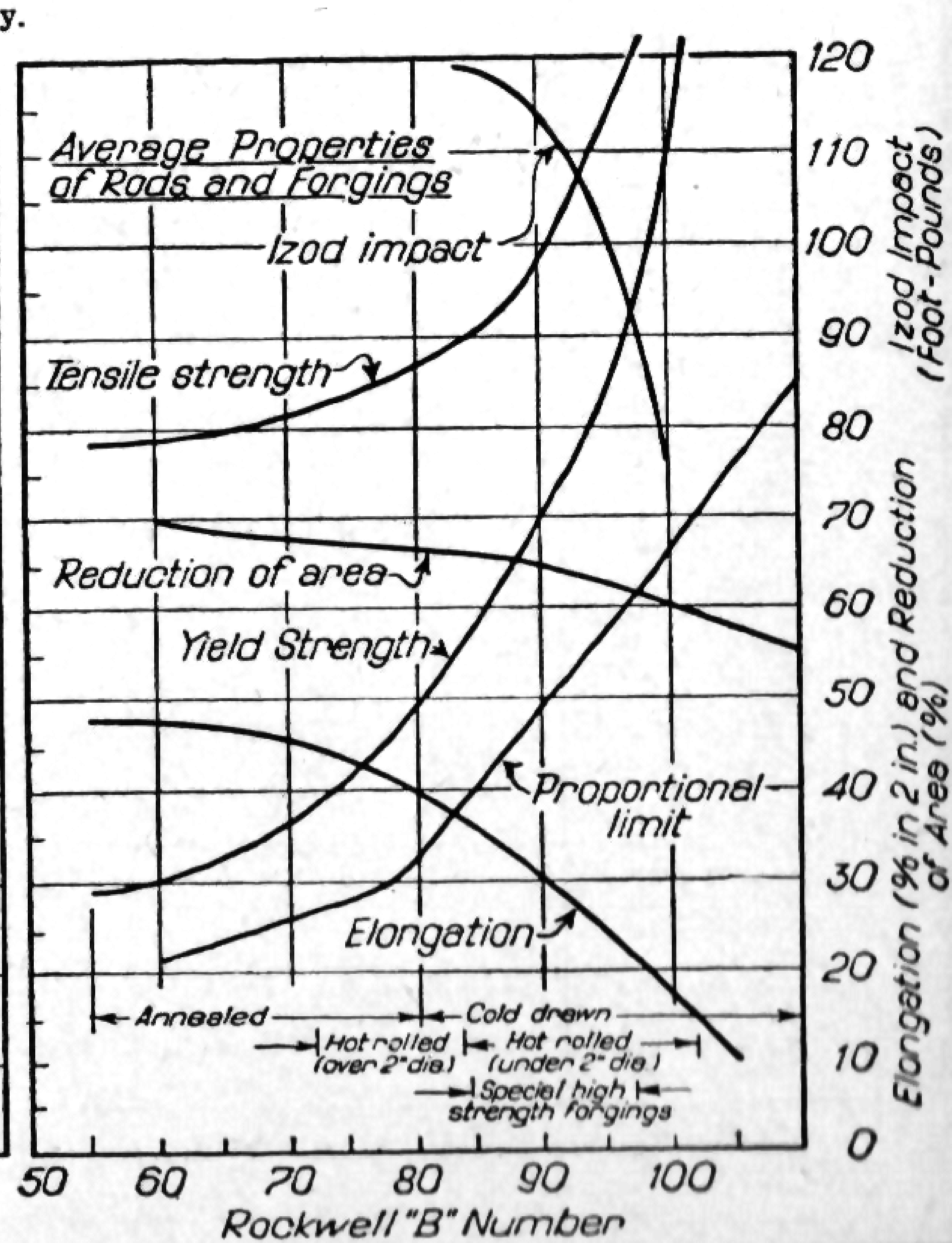
Specific gravity	8.84
Density, lb. per cu.in.	0.319
Melting range	
degrees F.	2370 to 2460
degrees C.	1300 to 1350
Specific heat at (80° to 212° F.) (27° to 100° C.)	0.127
Heat expansion coefficient	
at 80° to 212° F., per °F.	0.0000078
at 25° to 100° C., per °C.	0.000014
Thermal conductivity	
at 80° to 212° F., B.t.u./sq.ft./hr. /° F./in.	180
at zero to 100° C., cal./sq.cm./sec. /° C./cm.	0.06
Electrical resistivity	
at 32° F., ohms/circ.mil.ft.	290
at 0° C., microhms/cm.^{3}	48.2
Temperature coefficient of electrical resistivity	
per ° F.	0.0011
per ° C.	0.0019
Modulus of elasticity	
in tension, psi.	26,000,000
in torsion, psi.	9,500,000
Poisson's ratio	0.32

Mechanical Properties of K Monel

Condition (K Monel)	Ultimate*	Yield (0.5% Set)*	Elongation	Reduction	Brinell
Soft, quenched from 1450° F	<120	<60	>40	>50	<200
Reheated to 1000° F.	120 to 140	80 to 100	>30	>35	225 to 275
Reheated to 1100° F.	140 to 160	100 to 120	>20	>25	275 to 325
Cold worked and reheated to 1100° F.	>160	>120	>15	>20	>325†

*In 1000 psi. †Machined only with difficulty.





Toolsteels Classified by Wear-Toughness Ratio

By Harold B. Chambers (See Metal Progress, June 1940, for Its Use as a Tool Selector)

Each of the three groups arranged in order of increasing toughness and decreasing wear resistance. Figures indicated as max. are optional and may be present up to amount noted. Since the difference in relative wear-toughness capacities of adjacent classes is small to negligible, the many brands covered by each class may be expected to give competitive performance except when highly standardized operating conditions require that consideration be given to the footnotes.

Class	Conventional Type Names	Carbon	Manganese	Silicon	Tungsten	Chromium	Vanadium	Molybdenum	Cobalt	Nickel	Notes
	Water Hardening Steels										
1A	Tungsten finishing	1.25-1.50	0.15-0.35	0.15-0.50	2.50- 6.00	1.80 max.	0.30 max.	0.50 max.			A,B,C
1B	Carbon or carbon-vanadium	1.30-1.45	0.15-0.35	0.15-0.35		0.35 max.	0.30 max.				A,C
2A	High carbon, low tungsten	1.10-1.30	0.15-0.35	0.15-0.35	1.00- 2.50	0.35 max.	0.30 max.				A,B
2B	Low chromium or chrome-vanadium	1.10-1.30	0.15-0.35	0.15-0.35		0.10- 1.20	0.30 max.				A,C
2C	Carbon or carbon-vanadium	1.10-1.30	0.15-0.35	0.15-0.35			0.30 max.				A
3A	High carbon, low tungsten	0.90-1.10	0.15-0.35	0.15-0.35	1.00- 2.50	0.75 max.	0.30 max.				A,B,C
3B	Low chromium or chrome-vanadium	0.90-1.10	0.15-0.35	0.15-0.35		0.10- 1.50	0.30 max.				A,C
3C	Carbon or carbon-vanadium	0.90-1.10	0.15-0.35	0.15-0.50			0.50 max.				A,D
4A	Chrome-molybdenum or chrome-vanadium	0.55-0.90	0.15-0.35	0.15-0.35		0.40- 1.20	0.35 max.	0.25 max.		0.50 max.	A,C
4B	Carbon or carbon-vanadium	0.70-0.90	0.15-0.35	0.15-0.35			0.30 max.				A
4C	Silico-manganese or silico-molybdenum	0.45-0.75	0.35-1.00	0.75-2.25		0.60 max.	0.35 max.	0.60 max.			A,E
	Oil Hardening and Air Hardening Steels (Tools of Intricate Design)										
5A	High carbon, high chromium	1.80-2.50	0.15-1.20	0.15-1.00	2.00 max.	10.50-14.00	1.25 max.	0.30 max.	1.00 max.	1.00 max.	A,F,G
5B	High carbon, high chromium	1.80-2.40	0.15-0.60	0.15-0.50		10.50-14.00	1.20 max.	0.70- 1.00	0.60 max.		A,F,G
5C	High carbon, high chromium	1.30-1.70	0.15-0.60	0.15-0.50		10.50-14.00	1.20 max.	0.50- 1.25	4.00 max.	1.00 max.	A,F,G
5D	High carbon, high chromium	1.10-1.40	0.15-1.20	0.15-1.10		5.00-13.00	0.75 max.	0.70- 1.50	0.60 max.		A,F,G
6A	Chrome-molybdenum	1.10-1.30	0.35-0.95	0.15-0.35		0.40- 1.75		0.25- 0.75			A,E
6B	High carbon, low tungsten	1.10-1.30	0.15-0.70	0.15-0.35	1.00- 2.50	0.35- 1.25	0.30 max.				A,B,C
6C	Low chromium or chrome-vanadium	1.10-1.30	0.35-0.70	0.15-0.35		0.40- 1.50	0.30 max.				A,C
7A	Cr-Mo, Mn-Cr. or Mn-Mo non-deforming	0.80-1.10	0.35-3.25	0.15-1.00		0.80- 5.50	0.50 max.	0.75-1.75			A,E
7B	Chromium non-deforming	0.90-1.10	0.35-1.10	0.15-0.50	1.10 max.	0.90- 1.60	0.30 max.	0.50 max.			A,E
7C	Manganese non-deforming	0.80-1.10	0.85-1.80	0.15-0.50	0.70 max.	0.90 max.	0.30 max.	0.35 max.			A,E
8A	Low tungsten-chromium	0.40-0.65	0.15-0.35	0.15-1.50	0.75- 3.00	0.50- 2.00	0.50 max.	0.35 max.		1.50 max.	A,E
8B	Chrome-nickel or chrome-nickel-molybdenum	0.50-0.80	0.35-0.90	0.15-0.35		0.50- 1.25	0.30 max.	0.80 max.		1.00-2.50	A,E
8C	Chrome-molybdenum, chrome-vanadium, or manganese-molybdenum	0.50-0.90	0.35-0.90	0.15-0.50		1.20 max.	0.35 max.	0.40 max.		0.50 max.	A,E
8D	Silico-molybdenum	0.45-0.60	0.35-1.25	0.75-2.25	0.50 max.	0.75 max.	0.60 max.	0.15- 2.20			A,E
	High Speed (H.S.) Steels and Hot Work (H.W.) Steels (Tools Which Heat Up)										
9A	Tungsten-cobalt high speed	0.65-0.90	0.15-0.35	0.15-0.50	18.00-23.00	3.50- 4.75	1.00-3.00	1.25 max.	9.00-15.00		A,G,H
9B	Tungsten-cobalt high speed	0.65-0.90	0.15-0.35	0.15-0.50	17.00-21.00	3.50- 4.75	1.00-2.50	1.25 max.	5.00- 9.00		A,G,H
9C	Tungsten-cobalt high speed	0.65-0.80	0.15-0.35	0.15-0.50	17.00-20.00	3.50- 4.75	0.75-1.50	1.00 max.	2.00- 5.00		A,G,H
9D	Tungsten-cobalt high speed	0.65-0.85	0.15-0.35	0.15-0.50	12.00-15.00	3.50- 4.75	1.00-2.25	0.75 max.	3.00- 8.00		A,G,H
9E*	Molybdenum-cobalt H.S.	0.75-0.95	0.15-0.35	0.15-0.50	6.50 max.	3.50- 4.75	1.00-2.50	4.00-10.00	2.00- 9.00		A,G,H
10A	18-4-4 and 18-4-3 high speed	0.90-1.30	0.15-0.35	0.15-0.50	17.00-19.00	3.50- 4.75	2.50-4.25	1.00 max.			A,H
10B	18-4-2 high speed	0.75-0.90	0.15-0.35	0.15-0.50	17.00-19.00	3.50- 4.75	1.50-2.50	1.00 max.			A,H
10C	18-4-1 high speed	0.55-0.80	0.15-0.35	0.15-0.75	16.00-21.00	3.50- 4.75	0.50-1.50				A,H
10D	14-4-2 and 14-4-1 high speed	0.55-0.80	0.15-0.35	0.15-0.50	13.00-15.00	3.50- 4.75	0.75-2.25				A,H
10E*	Mo-W or Mo-V high speed	0.65-1.30	0.15-0.35	0.15-0.50	6.50 max.	3.50- 4.75	0.75-4.25	4.00- 9.50			A,H
11A	Low carbon high speed	0.45-0.60	0.15-0.35	0.15-0.35	16.00-19.00	3.00- 4.50	0.50-1.25				A,H,I
11B	High tungsten hot work	0.25-0.60	0.15-0.35	0.15-0.35	12.00-16.00	2.50- 4.50	0.75 max.	2.50 max.		3.00 max.	A,H,I
11C	Tungsten hot work	0.25-0.50	0.15-0.35	0.15-0.35	8.00-12.00	1.25- 3.50	0.60 max.	1.00 max.	2.00 max.	2.25 max.	A,H,I
11D*	Mo. or Mo-W hot work	0.30-0.65	0.15-0.35	0.15-1.75	3.00 max.	2.00- 5.50	1.25 max.	2.50 -9.00		1.75 max.	A,H,I
11E	Tungsten-chromium H.W.	0.30-0.60	0.15-0.75	0.35-1.75	4.00- 7.50	4.50- 7.50	0.60 max.	1.00 max.	0.60 max.	0.50 max.	A,H,I
12A	Chrome-molybdenum H.W.	0.30-0.60	0.15-1.25	0.80-1.10	1.75 max.	4.00- 7.50	0.50 max.	0.45- 3.00	0.60 max.	2.00 max.	A,H
12B	Low tungsten-chromium H.W.	0.35-0.65	0.15-0.80	0.15-1.10	1.50- 4.25	0.75- 3.50	0.50 max.	0.60 max.		1.50 max.	A,H
12C	Chrome-molybdenum H.W. or chromium hot work	0.30-1.00	0.15-0.75	0.15-0.75	1.00 max.	2.25- 4.50	1.00 max.	1.00 max.		0.50 max.	A,H
12D	Cr-Ni, or Cr-Ni-Mo hot work	0.25-0.60	0.15-1.00	0.15-0.35		0.50- 2.50	0.30 max.	1.25 max.		1.25-5.00	A,H

A. Wear resistance increases and toughness decreases as carbon content increases.
B. Wear resistance increases and toughness decreases as tungsten content increases.
C. Hardenability increases, wear resistance increases, toughness decreases, movement in hardening decreases, and tendency for soft spots in hardening decreases as chromium increases.
D. Some special applications (silverware striking dies, certain header dies, etc.) may occasionally require extra penetration of hardness, which may be produced by adjusting manganese and silicon contents.
E. Hardenability increases, wear resistance increases and toughness decreases as total alloy content increases.
F. Machining difficulties increase as total alloy content increases.
G. Red hardness properties increase and toughness decreases as cobalt content increases.
H. Red hardness properties increase and toughness decreases as total alloy content increases.
I. Water cooling surface in operation, particularly when intermittent, tends to promote heat checking approximately in proportion to tungsten and/or molybdenum content.

*Not divided into classes. The relative position of a specific molybdenum steel is just below its tungsten steel counterpart. The tungsten counterpart is indicated by adding twice the molybdenum content to the tungsten in a molybdenum steel having 0.05-0.10% higher carbon than the tungsten steel.

Approximate Density of Materials

[At 20C (68F), unless otherwise noted]

Material	Lb per Cu Ft	Specific Gravity (H_2O = 1)
Aluminum	165	2.65
Aluminum, wrought	168.6	2.7
Antimony	413	6.62
Asbestos Board	75	1.2
Balsa	9	0.14
Benzene	56.1	0.9
Bismuth	612	9.8
Brass, cast	527	8.44
Brass, wire	543	8.7
Bronze	555	8.89
Constantan	554	8.88
Copper	555	8.89
Copper, cast	530	8.49
Cork	15	0.24
Ebonite	72	1.15
Ether, sulphuric	46	0.74
German Silver	536	8.59
Glass	162	2.6
Gold	1206	19.32
Granite	168	2.69
Iron, gray cast	442	7.09
Iron, wrought	490	7.85
Lead	708	11.34
Magnalium	125	2.0
Magnesium	108.7	1.74
Mercury, fluid	846	13.55
Molybdenum	637	10.2
Naphtha	42	0.67
Nickel	545	8.74
Nitric Acid	94	1.51
Oak	46	0.74
Oil, linseed	58.8	0.94
Oil, turpentine	54.3	0.87
Paper	58	0.93
Petroleum	54	0.87
Phosphor Bronze	555	8.89
Platinum	1340	21.46
Sandstone	140	2.24
Silver	656	10.51
Steel	489	7.83
Sulphuric Acid (conc.)	112.3	1.8
Textolite (thermosetting)	103	1.65
Textolite (thermoplastic)	81	1.3
Tin	455	7.29
Tungsten	1206	19.32
Walnut	41	0.66
Water (H_2O), pure (4C)	62.43	1.0
White Pine	26	0.42
Zinc	443	7.1

Temperature Conversions

Albert Sauveur type of table. Look up reading in middle column; if in degrees Centigrade, read Fahrenheit equivalent in right hand column; if in degrees Fahrenheit, read Centigrade equivalent in left hand column. Values as printed in "Bethlehem Alloy Steels".

-459.4 to 0			0 to 100						100 to 1000						1000 to 2000						2000 to 3000					
C		F	C		F	C		F	C		F	C		F	C		F	C		F	C		F	C		F
-273	-459.4		-17.8	0	32	10.0	50	122.0	38	100	212	260	500	932	538	1000	1832	816	1500	2732	1093	2000	3632	1371	2500	4532
-268	-450		-17.2	1	33.8	10.6	51	123.8	43	110	230	266	510	950	543	1010	1850	821	1510	2750	1099	2010	3650	1377	2510	4550
-262	-440		-16.7	2	35.6	11.1	52	125.6	49	120	248	271	520	968	549	1020	1868	827	1520	2768	1104	2020	3668	1382	2520	4568
-257	-430		-16.1	3	37.4	11.7	53	127.4	54	130	266	277	530	986	554	1030	1886	832	1530	2786	1110	2030	3686	1388	2530	4586
-251	-420		-15.6	4	39.2	12.2	54	129.2	60	140	284	282	540	1004	560	1040	1904	838	1540	2804	1116	2040	3704	1393	2540	4604
-246	-410		-15.0	5	41.0	12.8	55	131.0	66	150	302	288	550	1022	566	1050	1922	843	1550	2822	1121	2050	3722	1399	2550	4622
-240	-400		-14.4	6	42.8	13.3	56	132.8	71	160	320	293	560	1040	571	1060	1940	849	1560	2840	1127	2060	3740	1404	2560	4640
-234	-390		-13.9	7	44.6	13.9	57	134.6	77	170	338	299	570	1058	577	1070	1958	854	1570	2858	1132	2070	3758	1410	2570	4658
-229	-380		-13.3	8	46.4	14.4	58	136.4	82	180	356	304	580	1076	582	1080	1976	860	1580	2876	1138	2080	3776	1416	2580	4676
-223	-370		-12.8	9	48.2	15.0	59	138.2	88	190	374	310	590	1094	588	1090	1994	866	1590	2894	1143	2090	3794	1421	2590	4694
-218	-360		-12.2	10	50.0	15.6	60	140.0	93	200	392	316	600	1112	593	1100	2012	871	1600	2912	1149	2100	3812	1427	2600	4712
-212	-350		-11.7	11	51.8	16.1	61	141.8	99	210	410	321	610	1130	599	1110	2030	877	1610	2930	1154	2110	3830	1432	2610	4730
-207	-340		-11.1	12	53.6	16.7	62	143.6	100	212	413.6	327	620	1148	604	1120	2048	882	1620	2948	1160	2120	3848	1438	2620	4748
-201	-330		-10.6	13	55.4	17.2	63	145.4	104	220	428	332	630	1166	610	1130	2066	888	1630	2966	1166	2130	3866	1443	2630	4766
-196	-320		-10.0	14	57.2	17.8	64	147.2	110	230	446	338	640	1184	616	1140	2084	893	1640	2984	1171	2140	3884	1449	2640	4784
-190	-310		-9.4	15	59.0	18.3	65	149.0	116	240	464	343	650	1202	621	1150	2102	899	1650	3002	1177	2150	3902	1454	2650	4802
-184	-300		-8.9	16	60.8	18.9	66	150.8	121	250	482	349	660	1220	627	1160	2120	904	1660	3020	1182	2160	3920	1460	2660	4820
-179	-290		-8.3	17	62.6	19.4	67	152.6	127	260	500	354	670	1238	632	1170	2138	910	1670	3038	1188	2170	3938	1466	2670	4838
-173	-280		-7.8	18	64.4	20.0	68	154.4	132	270	518	360	680	1256	638	1180	2156	916	1680	3056	1193	2180	3956	1471	2680	4856
-169	-273	-459.4	-7.2	19	66.2	20.6	69	156.2	138	280	536	366	690	1274	643	1190	2174	921	1690	3074	1199	2190	3974	1477	2690	4874
-168	-270	-454	-6.7	20	68.0	21.1	70	158.0	143	290	554	371	700	1292	649	1200	2192	927	1700	3092	1204	2200	3992	1482	2700	4892
-162	-260	-436	-6.1	21	69.8	21.7	71	159.8	149	300	572	377	710	1310	654	1210	2210	932	1710	3110	1210	2210	4010	1488	2710	4910
-157	-250	-418	-5.6	22	71.6	22.2	72	161.6	154	310	590	382	720	1328	660	1220	2228	938	1720	3128	1216	2220	4028	1493	2720	4928
-151	-240	-400	-5.0	23	73.4	22.8	73	163.4	160	320	608	388	730	1346	666	1230	2246	943	1730	3146	1221	2230	4046	1499	2730	4946
-146	-230	-382	-4.4	24	75.2	23.3	74	165.2	166	330	626	393	740	1364	671	1240	2264	949	1740	3164	1227	2240	4064	1504	2740	4964
-140	-220	-364	-3.9	25	77.0	23.9	75	167.0	171	340	644	399	750	1382	677	1250	2282	954	1750	3182	1232	2250	4082	1510	2750	4982
-134	-210	-346	-3.3	26	78.8	24.4	76	168.8	177	350	662	404	760	1400	682	1260	2300	960	1760	3200	1238	2260	4100	1516	2760	5000
-129	-200	-328	-2.8	27	80.6	25.0	77	170.6	182	360	680	410	770	1418	688	1270	2318	966	1770	3218	1243	2270	4118	1521	2770	5018
-123	-190	-310	-2.2	28	82.4	25.6	78	172.4	188	370	698	416	780	1436	693	1280	2336	971	1780	3236	1249	2280	4136	1527	2780	5036
-118	-180	-292	-1.7	29	84.2	26.1	79	174.2	193	380	716	421	790	1454	699	1290	2354	977	1790	3254	1254	2290	4154	1532	2790	5054
-112	-170	-274	-1.1	30	86.0	26.7	80	176.0	199	390	734	427	800	1472	704	1300	2372	982	1800	3272	1260	2300	4172	1538	2800	5072
-107	-160	-256	-0.6	31	87.8	27.2	81	177.8	204	400	752	432	810	1490	710	1310	2390	988	1810	3290	1266	2310	4190	1543	2810	5090
-101	-150	-238	0.0	32	89.6	27.8	82	179.6	210	410	770	438	820	1508	716	1320	2408	993	1820	3308	1271	2320	4208	1549	2820	5108
-96	-140	-220	0.6	33	91.4	28.3	83	181.4	216	420	788	443	830	1526	721	1330	2426	999	1830	3326	1277	2330	4226	1554	2830	5126
-90	-130	-202	1.1	34	93.2	28.9	84	183.2	221	430	806	449	840	1544	727	1340	2444	1004	1840	3344	1282	2340	4244	1560	2840	5144
-84	-120	-184	1.7	35	95.0	29.4	85	185.0	227	440	824	454	850	1562	732	1350	2462	1010	1850	3362	1288	2350	4262	1566	2850	5162
-79	-110	-166	2.2	36	96.8	30.0	86	186.8	232	450	842	460	860	1580	738	1360	2480	1016	1860	3380	1293	2360	4280	1571	2860	5180
-73	-100	-148	2.8	37	98.6	30.6	87	188.6	238	460	860	466	870	1598	743	1370	2498	1021	1870	3398	1299	2370	4298	1577	2870	5198
-68	-90	-130	3.3	38	100.4	31.1	88	190.4	243	470	878	471	880	1616	749	1380	2516	1027	1880	3416	1304	2380	4316	1582	2880	5216
-62	-80	-112	3.9	39	102.2	31.7	89	192.2	249	480	896	477	890	1634	754	1390	2534	1032	1890	3434	1310	2390	4334	1588	2890	5234
-57	-70	-94	4.4	40	104.0	32.2	90	194.0	254	490	914	482	900	1652	760	1400	2552	1038	1900	3452	1316	2400	4352	1593	2900	5252
-51	-60	-76	5.0	41	105.8	32.8	91	195.8				488	910	1670	766	1410	2570	1043	1910	3470	1321	2410	4370	1599	2910	5270
-46	-50	-58	5.6	42	107.6	33.3	92	197.6				493	920	1688	771	1420	2588	1049	1920	3488	1327	2420	4388	1604	2920	5288
-40	-40	-40	6.1	43	109.4	33.9	93	199.4				499	930	1706	777	1430	2606	1054	1930	3506	1332	2430	4406	1610	2930	5306
-34	-30	-22	6.7	44	111.2	34.4	94	201.2				504	940	1724	782	1440	2624	1060	1940	3524	1338	2440	4424	1616	2940	5324
-29	-20	-4	7.2	45	113.0	35.0	95	203.0				510	950	1742	788	1450	2642	1066	1950	3542	1343	2450	4442	1621	2950	5342
-23	-10	14	7.8	46	114.8	35.6	96	204.8				516	960	1760	793	1460	2660	1071	1960	3560	1349	2460	4460	1627	2960	5360
-17.8	0	32	8.3	47	116.6	36.1	97	206.6				521	970	1778	799	1470	2678	1077	1970	3578	1354	2470	4478	1632	2970	5378
			8.9	48	118.4	36.7	98	208.4				527	980	1796	804	1480	2696	1082	1980	3596	1360	2480	4496	1638	2980	5396
			9.4	49	120.2	37.2	99	210.2				532	990	1814	810	1490	2714	1088	1990	3614	1366	2490	4514	1643	2990	5414
						37.8	100	212.0				538	1000	1832				1093	2000	3632				1649	3000	5432

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